

AD-A267 466

2. REPORT DATE
19933. REPORT TYPE AND DATES COVERED
THESIS/DOSSIER/WORK

4. TITLE AND SUBTITLE

Pneumatically-Powered Orthosis and Electronic Control
System for Stroke Patient Rehabilitation

5. FUNDING NUMBERS

6. AUTHOR(S)

Capt William K. Brogran, Jr

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

AFIT Student Attending: University of California-San Diego

8. PERFORMING ORGANIZATION
REPORT NUMBER

AFIT/CI/CIA- 93-002

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFIT/CI
Wright-Patterson AFB OH 45433-658310. SPONSORING / MONITORING
AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

DTIC
ELECTE
S AUG 6 1993 D
c

12a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release IAW 190-1
Distribution Unlimited
MICHAEL M. BRICKER, SMSgt, USAF
Chief Administration

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

93 8 05 164

93-18111

14. SUBJECT TERMS

15. NUMBER OF PAGES

97

16. PRICE CODE

17. SECURITY CLASSIFICATION
OF REPORT18. SECURITY CLASSIFICATION
OF THIS PAGE19. SECURITY CLASSIFICATION
OF ABSTRACT

20. LIMITATION OF ABSTRACT

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Pneumatically-Powered Orthosis and Electronic Control System for Stroke Patient Rehabilitation

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science
in Engineering Sciences (Systems Science)

by

William K. Brogan, Jr.

Captain, USAF

DTIC QUALITY INSPECTED 3

TOTAL NUMBER OF PAGES = 97

Committee in Charge:

Alan M. Schneider, Sc.D., Chair
Richard L. Lieber, Ph.D.
Shu Chien, M.D., Ph.D.

1993

Accession For	
NTIS - CRA&I	<input checked="" type="checkbox"/>
DTIC - TAB	<input type="checkbox"/>
Unannounced	<input type="checkbox"/>
Justification	
By	
Distribution /	
Availability Codes	
Dist	Avail and/or Special
A-1	

ABSTRACT OF THE THESIS

Pneumatically-Powered Orthosis and Electronic Control System for Stroke Patient Rehabilitation

by

William K. Brogan, Jr.
Master of Science in Engineering Sciences (Systems Science)
University of California, San Diego, 1993

Dr. Alan M. Schneider, Chair

This thesis presents the development of a system designed to manipulate the upper extremity of stroke patients suffering from hemiplegia. The orthosis, an aluminum structure built to be strapped onto a patient's paretic arm, is jointed at the elbow to allow rotational motion of the arm. Compressed air provides the force necessary to move the orthosis/arm combination through a selected motion profile via a power cylinder activated by a pneumatic servovalve. Sensors located on the orthosis and throughout the system provide feedback to circuitry which precisely controls arm position.

A digital computer with data acquisition capability provides software control over several system parameters and generates a user-friendly interface to the therapist performing the rehabilitation exercise. Measurements such as velocity, acceleration, and differential pressure taken during various operating modes can be used to calculate power, strength, range of motion, and degree of muscle spasticity so that a time history of improvement for the patient may be developed and used to study the effects of such therapy on stroke rehabilitation.

REFERENCES

- [1] Vernon L. Nickel, M.D., M.Sc., retired Professor of Surgery for the University of California, San Diego Medical School (Orthopedics and Rehabilitation) and Director of Rehabilitation at the Sharp Rehabilitation Center in San Diego.
- [2] Isaka, S., Schneider, A., Filia, P., Lue, K., Coutts, R., Nickel, V., "*A New Tool for Stroke Rehabilitation Study*," proceedings of RESNA 10th Annual Conference, San Jose, CA, 1987.
- [3] Blevins, F., Coutts, R., Lieber, R., Schneider, A., Guier, C., Rosenstein, A., Stewart, W., Filia, P., Nickel, V., "*The Effect of Patterning Using Continuous Passive Motion on Stroke Rehabilitation*," proceedings of 34th Annual Meeting, Orthopaedic Research Society, February 1-4, 1988, Atlanta, Georgia.
- [4] S. Gordon, "*Servo Control of Pneumatic Systems Is Here*," Hydraulics & Pneumatics, July 1991.
- [5] deSilva, Clarence W., Control Sensors and Actuators, Prentice Hall, 1989.
- [6] Richard Duder, Vice President of Engineering, Dynamic Valves, Incorporated, 923 Industrial Avenue, Palo Alto, CA 94303. Phone: (800) 227-8825.
- [7] Operations manual for Model 23-7030A Servovalve Control Amplifier, Dynamic Valves, Inc.
- [8] Ogata, Katsohiko, Modern Control Engineering, second edition, Prentice Hall, 1990.
- [9] McCloy, D. and H.R. Martin, The Control of Fluid Power, John Wiley & Sons, 1973.
- [10] Operations manual for Keithley-Metrabyte DAS-16F Data Acquisition Board.
- [11] Reference manual for the GW BASIC programming language, AT&T and Microsoft, Inc., 1984.

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Pneumatically-Powered Orthosis and Electronic Control System for Stroke Patient Rehabilitation

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science
in Engineering Sciences (Systems Science)

by

William K. Brogan, Jr.

Committee in Charge:

Alan M. Schneider, Sc.D., Chair
Richard L. Lieber, Ph.D.
Shu Chien, M.D., Ph.D.

1993

UNIVERSITY OF CALIFORNIA, SAN DIEGO

Pneumatically-Powered Orthosis and Electronic Control System for Stroke Patient Rehabilitation

A thesis submitted in partial satisfaction of the
requirements for the degree Master of Science
in Engineering Sciences (Systems Science)

by

William K. Brogan, Jr.

Committee in Charge:

Alan M. Schneider, Sc.D., Chair
Richard L. Lieber, Ph.D.
Shu Chien, M.D., Ph.D.


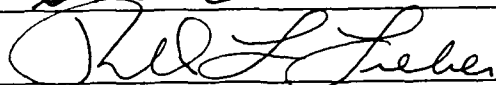
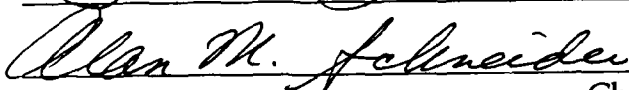
1993

Copyright

William K. Brogan, Jr., 1993

All rights reserved.

The thesis of William K. Brogan, Jr. is approved:




Chair

University of California, San Diego

1993

Table of Contents

Signature Page	iii
Table of Contents	iv
List of Figures	v
Acknowledgements	vi
Abstract	vii
I. Introduction and Background	1
II. Design Approach and Development	8
III. Detailed Design	11
A. Mechanical System	11
B. Control System	19
IV. System Testing and Analysis	32
V. Digital Computer Interface	52
VI. Safety Engineering	60
VII. Ideas for Further Improvement	62
VIII. Conclusion	67
Appendices	
A. Experimental frequency response plots	68
B. Root locus analyses of experimentally- derived system transfer functions	72
C. Software listings and descriptions	77
References	90

List of Figures

Figure 1.	Robotic orthosis with computer and equipment chassis	5
Figure 2.	Orthosis	12
Figure 3.	Orthosis positional geometry	13
Figure 4.	Orthosis diagram showing variables used in calculations	15
Figure 5.	Basic closed-loop position control system	21
Figure 6.	Schematic of four-way servovalve and air cylinder	22
Figure 7.	Block diagram of position and pressure feedback control	24
Figure 8.	Pneumatic cylinder showing unequal chamber pressures but equal force	26
Figure 9.	Summing amplifier circuit for position control loop	27
Figure 10.	Closed-loop frequency response test configuration	34
Figure 11.	Open-loop frequency response test configuration	37
Figure 12.	Gain values for system amplifiers	40
Figure 13.	Block diagram of system with position feedback only	43
Figure 14.	Breakdown of orthosis pneumatic/mechanical dynamics	46
Figure 15.	System block diagram	47
Figure 16.	Simplified system block diagram	49
Figure 17.	Data acquisition board output signal conditioning circuit	54
Figure 18.	System block diagram showing digital computer interface . . .	56

Acknowledgements

I am very grateful to Dr. Alan Schneider for providing me the opportunity to develop this project from an idea to a working model, spending many hours helping me to realize practical applications of control system theory. Many thanks also to the UCSD Academic Senate for approving our proposal and funding this research.

Eric Rollins, an engineering student, has been instrumental in the progress of this research by designing and manufacturing the structure of the orthosis as well as many other custom parts, and is responsible for converting each of the figures in the body of this document from a crude sketch to a computer graphic.

I also wish to acknowledge Tom Phillips, AMES Electronics Technician, for superior assistance in designing, building, and testing much of the circuitry required to operate the robotic arm.

I would like to thank my wonderful parents for their loving support and my father especially for spending countless hours with me editing and formatting this document. Thanks also go to Jim Braun for providing the computer and software necessary to publish this document.

Finally, special acknowledgement is deserved by the most important person in my life, Brenda Jean Brogan, who not only provided extra motivation and support throughout my Master's program, but who also gave me the most beautiful daughter in the world last summer, Kristin Ann. I love you both very much.

ABSTRACT OF THE THESIS

Pneumatically-Powered Orthosis and Electronic Control System for Stroke Patient Rehabilitation

by

William K. Brogan, Jr.

Master of Science in Engineering Sciences (Systems Science)

University of California, San Diego, 1993

Dr. Alan M. Schneider, Chair

This thesis presents the development of a system designed to manipulate the upper extremity of stroke patients suffering from hemiplegia. The orthosis, an aluminum structure built to be strapped onto a patient's paretic arm, is jointed at the elbow to allow rotational motion of the arm. Compressed air provides the force necessary to move the orthosis/arm combination through a selected motion profile via a power cylinder activated by a pneumatic servovalve. Sensors located on the orthosis and throughout the system provide feedback to circuitry which precisely controls arm position.

A digital computer with data acquisition capability provides software control over several system parameters and generates a user-friendly interface to the therapist performing the rehabilitation exercise. Measurements such as velocity, acceleration, and differential pressure taken during various operating modes can be used to calculate power, strength, range of motion, and degree of muscle spasticity so that a time history of improvement for the patient may be developed and used to study the effects of such therapy on stroke rehabilitation.

I. INTRODUCTION AND BACKGROUND

Hundreds of thousands of Americans become victims of a disabling stroke each year. Although many are too severely affected to benefit from standard rehabilitation therapy, most patients will benefit from such therapy in varying degrees. Stroke often leaves its victim suffering from hemiplegia, paralysis of one half of the body. Current rehabilitative techniques include passive motion of the patient's unresponsive limb to improve range of motion and strength. However, there seems to be a lack of scientifically-gathered quantitative measurements dealing with stroke patient improvement over a course of time. This is the underlying premise on which my research and the development of the powered orthosis is based.

With our "robotic arm" orthosis, as I shall refer to it throughout this report, we will perform extensive studies of stroke patient improvement over time based on several measurable quantities recorded during therapy. Since this goal is a long-term one, this thesis only covers the design approach and preliminary testing of the mechanical and electronic systems of which the robotic arm is comprised. A later section will describe recommended additions and improvements to the system that will enable safe and practical use with actual stroke patients.

The original idea for this research came from Dr. Vernon L. Nickel [1], retired Director of Rehabilitation at Sharp Rehabilitation Center, who suggested that continuous passive motion of a stroke patient's disabled limb could possibly increase the effectiveness of and shorten the ensuing recovery period. Research

involving continuous passive motion (one of the functions this robotic orthosis will provide) for the rehabilitation of a stroke victim's dysfunctional upper extremity, together with quantitative measurements of progress, is almost non-existent. The mechanism of continuous passive motion (CPM) in stroke patient rehabilitation has not been fully exploited, although several studies have been performed by associates of the University. However, these studies concentrated on the lower extremities. In previous work, Dr. Schneider and others developed a computer program that complemented a continuous passive motion device built by a San Diego biomedical company for exercising and training the leg of a stroke patient. [2] Favorable results from its use in a test with 31 patients are described in a short paper by Blevins, Coutts, Lieber, Schneider, et. al. [3] Up to the present time, over 100 patients have used this machine at Sharp Hospital, San Diego, under the direction of Richard D. Coutts, M.D.

The "robotic arm" prototype as it currently exists is a machined aluminum frame structure, hinged at the elbow, which can be strapped around a patient's forearm and upper arm (see Figure 1). The forearm and upper arm sections move relative to each other with the positioning force provided by a pneumatic (air) cylinder. A similar-looking cylinder attached onto this power cylinder is a linear potentiometer which provides a feedback voltage relative to the position of the pneumatic cylinder rod. The compressed air required to power the cylinder is provided by facility connections at a pressure of 80 pounds per square inch (psi). This air is fed through a mist separator to remove excessive moisture, then

directly to the controlling component, called a pneumatic servovalve. The servovalve is an electro-pneumatic device which uses a varying input voltage produced by the electronic control system to output a proportional rate of air flow to the air cylinder. This is the key ingredient in the ability of the system to position the arm precisely to where it is commanded. The electronic control system consists of the various devices and electrical signals required to generate a desired motion profile for the arm, measure the arm's actual position, and use any error between the two to cause the servovalve to correct the arm's position. Specifically, this system includes a commercially available analog servo control amplifier circuit designed to drive the servovalve, two pressure transducers (sensors) which provide a differential cylinder pressure feedback signal to this amplifier circuit, and position-sensing equipment used to generate the control signal required. A rotary encoder (used to determine rotation angle) located at the elbow joint and the linear potentiometer mentioned earlier provide different forms of position feedback, either of which can be compared with the desired position of the arm (based on a selected motion profile). A separate summing amplifier circuit performs this comparison and outputs the resulting error signal to the servo control amplifier circuit.

User-friendly, interactive software for an IBM-compatible personal computer exists in preliminary form to create a desired motion profile for the arm and will eventually be upgraded to perform the calculations necessary to determine patient exercise parameters such as strength, energy, power, and range

of motion. Results will be displayed graphically, permitting the exercise to be evaluated in real time, and will also be stored internally so that the progress over a course of therapy may be evaluated. The computer is able to control the motion of the arm through an internal data acquisition board which can not only output a continuous analog signal, but can also input analog data (i.e. from our pressure sensors) and convert it to the computer's digital format so that it can be manipulated with software to perform a variety of functions. Figure 1 shows the orthosis with its associated equipment chassis and digital computer.

This pneumatically-powered orthotic arm has been designed to accommodate four different modes of operation:

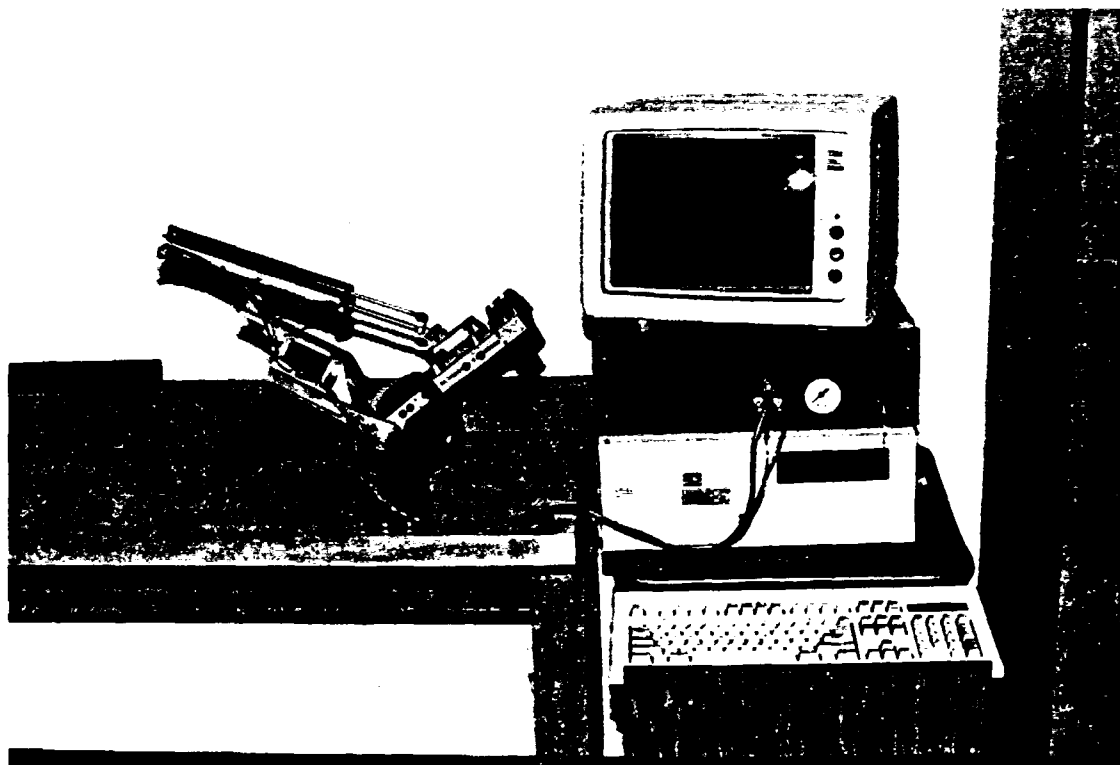
Mode 1: exercise mode, in which the patient is passive, and the arm cycles up and down continuously at a speed and through a range selected by the operator until commanded to stop.

Mode 2: assist mode, in which the patient must apply a certain percentage of the force required to raise his/her arm while the system applies the extra force necessary to put the arm in motion.

Mode 3: static evaluation mode, in which the patient applies as much force as possible at various fixed arm angles so that the computer can calculate strength.

Mode 4: dynamic evaluation mode, in which the patient moves his/her arm (if possible) without computer assistance so that range of motion, velocity, and power measurements can be taken.

Figure 1. Robotic orthosis with computer and equipment chassis



At the present time, the exercise mode (Mode 1) is fully functional. When the computer program is started, the therapist is prompted to strap the orthosis around the patient's arm then move the arm/orthosis combination to maximum flexion and extension angles to be achieved during the exercise. This angle data is generated by the rotary encoder and inserted into the exercise motion profile. Continuing prompts from the software ask the user for desired rate of motion, any rest time at each extreme position, and the number of exercise cycles to perform (one cycle defined as motion from the maximum extension angle to the maximum flexion angle and back to maximum extension). The arm is commanded to move at a constant speed to more closely resemble the motion applied by a physical therapist.

Mode 2, assist mode, is still being implemented but is conceptually defined. Since it can be calculated how much pressure in the cylinder is required to move the orthosis and patient arm, the operator will select a percentage of machine assistance from zero to one hundred which will preload the air cylinder with a proportional amount of pressure. The patient then only needs to put enough force into the orthosis to generate the remaining pressure in the cylinder which will consequently cause the arm to move. This mode will allow the patient to benefit from self-exercise at any level at which they are capable.

The static evaluation of Mode 3 has been partially demonstrated at this point by sending the output of the two pressure transducers (which measure pressure on both sides of the cylinder piston) to the computer and displaying a

time history of their difference as the arm is displaced from a static position. What is left to develop is the method by which this signal must be calibrated to accurately reflect the force exerted by the patient at that particular arm position.

For the dynamic evaluation required of Mode 4, in which we plan to either open the pneumatic system to minimize friction or remove the air cylinder altogether, we plan on taking patient range of motion, velocity, and power measurements using the data generated from the rotary encoder located at the elbow joint of the orthosis. Testing is under way to determine the optimum way to use computer-generated time pulses to get velocity and acceleration information from the encoder data. With this mode, as well as with the passive exercise mode, we may be able to take muscle spasticity measurements by sensing changes in acceleration and/or resistance using rotary encoder data and/or pressure transducer signals. These measurements, according to Dr. Lieber, would be useful in the study of stroke rehabilitation as they are presently not commonly taken.

Upon successful development of all four operating modes, a comprehensive effort will be undertaken to incorporate all possible safety features into the system. This will include, but not be limited to, mechanical stops to prevent hyperextension (already exist), speed control, air supply pressure control, emergency override switches (to stop motion), emergency release capability (to free patient), electrical/electronic failure protection, and software limit-checking.

II. DESIGN APPROACH AND DEVELOPMENT

Several options for powering the orthosis were considered during the conceptual design stage of this project. Electric motors were first discussed to directly drive the angular motion of the orthosis about the elbow joint, but a desire to minimize weight and protuberances prevented us from finding a suitable device. It was also recognized that a complex gearbox and/or clutch arrangement would be required in order to operate the orthosis in all of the planned modes, specifically the dynamic evaluation mode where all possible friction sources should be removed. Among the advantages of using a motor drive however are readily-available velocity feedback (with an attached tachometer), fewer system components, and a simpler system to analyze. Although the possibility of incorporating electric motors still remains a viable option, we decided to investigate other practical automation techniques.

The use of hydraulics was then considered because of its very high force output capability and ability for precise positioning control. However, it was determined that the very high pressures commonly found in hydraulic systems would prove to be a potential safety problem when used in such close proximity to human beings. Since a viscous fluid is used to transmit power in the system, we also felt that oil leaks would be inevitable, dangerous, and messy. Pricing components for a hydraulically controlled system revealed high costs which would have quickly depleted our budget.

We learned that several companies manufacture pneumatic servovalves, devices capable of using compressed air to produce the precise positioning required of our feedback control system. With a suitable electronic controller, a pneumatic servovalve can control a load with the accuracy normally only found in comparable hydraulic servo systems. Pneumatic systems however are limited to smaller loads since the standard maximum air pressure available is normally only 120 psi. We knew that the compressibility of air could present some problems, but decided to test a pneumatic servovalve and associated servo control amplifier anyway. Since compressed air was available via facility connections both in our engineering laboratory and in the Veterans Administration Medical Center physical therapy room, it was felt cost saving could be realized by requiring less machinery. For instance, a costly, loud, bulky air compressor is no longer required whereas it would have been if facility air was not available or if we had decided to use hydraulics. Consideration must be given to future locations where this system may be used, which may not have compressed air available through facility connections, such as in some rehabilitation clinics or smaller hospitals. This is one reason why the incorporation of electric motors may still be the best overall method of providing power to move the orthosis if the proper transmission system can be devised.

During the Spring quarter of 1992, a team consisting of four undergraduate engineering students (Eric Rollins, Steve Haase, Michelle Conlay, and Rick Batt) took initial requirements for design of the robotic arm from Dr. Schneider and myself and produced, over the course of an eight week class, the aluminum

orthosis structure and the circuitry for reading the elbow joint's optical encoder data. Complex initial specifications including wrist rotation and a master/slave concept using the patient's good arm to control the orthosis on the dysfunctional arm yielded to a more practical design involving just one degree of rotational freedom at the elbow joint. It was felt that once the mechanics and the control system were fully understood and developed for this approach, it would be more efficient to then incorporate more complex modifications.

My work with this robotic orthosis project has concentrated on using the student team's mechanical orthosis to design, develop, and integrate a suitable pneumatic control system so that the arm could eventually be used in the four desired modes previously mentioned.

III. DETAILED DESIGN

The robotic orthosis can be broken down into two major design categories: the mechanical system and the control system. Discussion of the digital interface will be deferred until Section V.

A. MECHANICAL SYSTEM

The primary mechanics of the orthosis at present include the hinged, aluminum structure itself as well as the linkage between the forearm and bicep sections provided by the pneumatic cylinder body and its piston rod (Figure 2). The device is allowed to rotate about the elbow joint with very low friction through use of high-precision ball bearings. The cylinder mounting locations on both sections of the orthosis are pin connections so that as the arm sweeps through its range of motion the pneumatic cylinder can freely adjust its relative position while its length varies. A 100-degree angular range of motion from full extension to full flexion was originally sought, but the geometry of the mounting locations and the cylinder size has limited us to about 93 degrees of arc. The cylinder body mounting collar may be used to adjust the maximum extension angle (and correspondingly the maximum flexion angle) while retaining the 93 degree range of motion. All analysis and initial testing were performed with the cylinder positioned so that the maximum extension occurred at zero degrees (when the forearm section and the bicep section are at an angle 180 degrees relative to each other). Refer to Figure 3 for a graphic description of the rotation

Figure 2. Orthosis

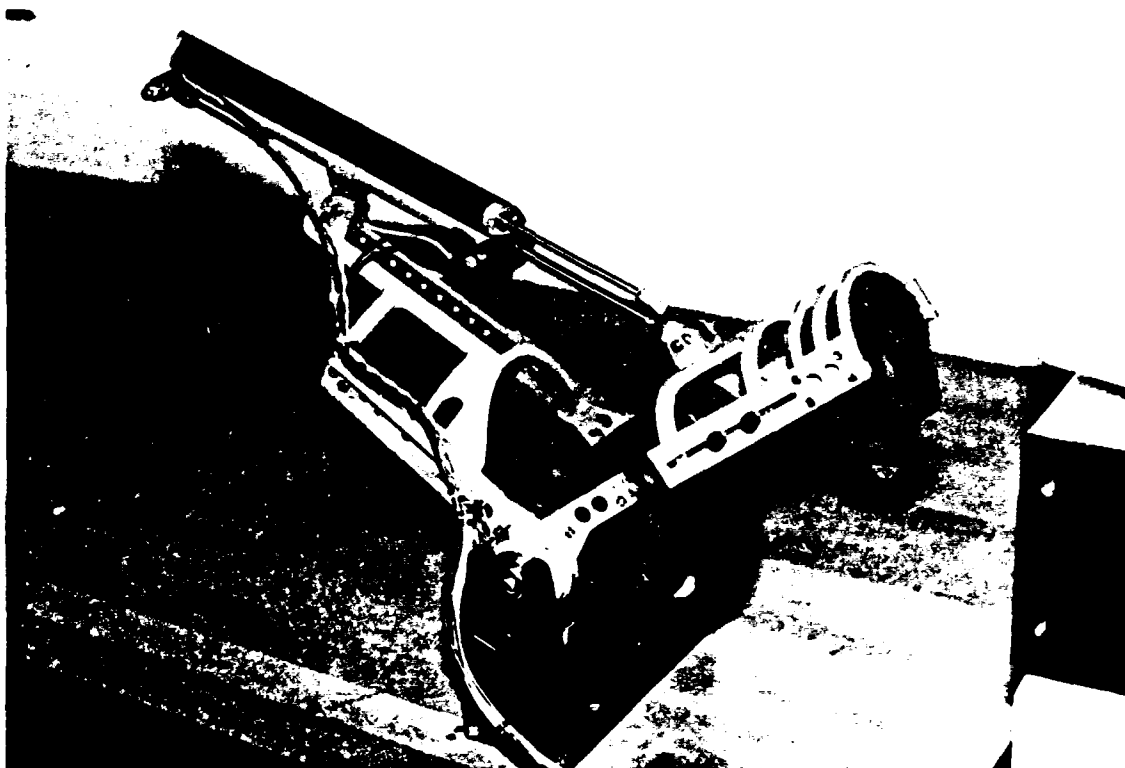
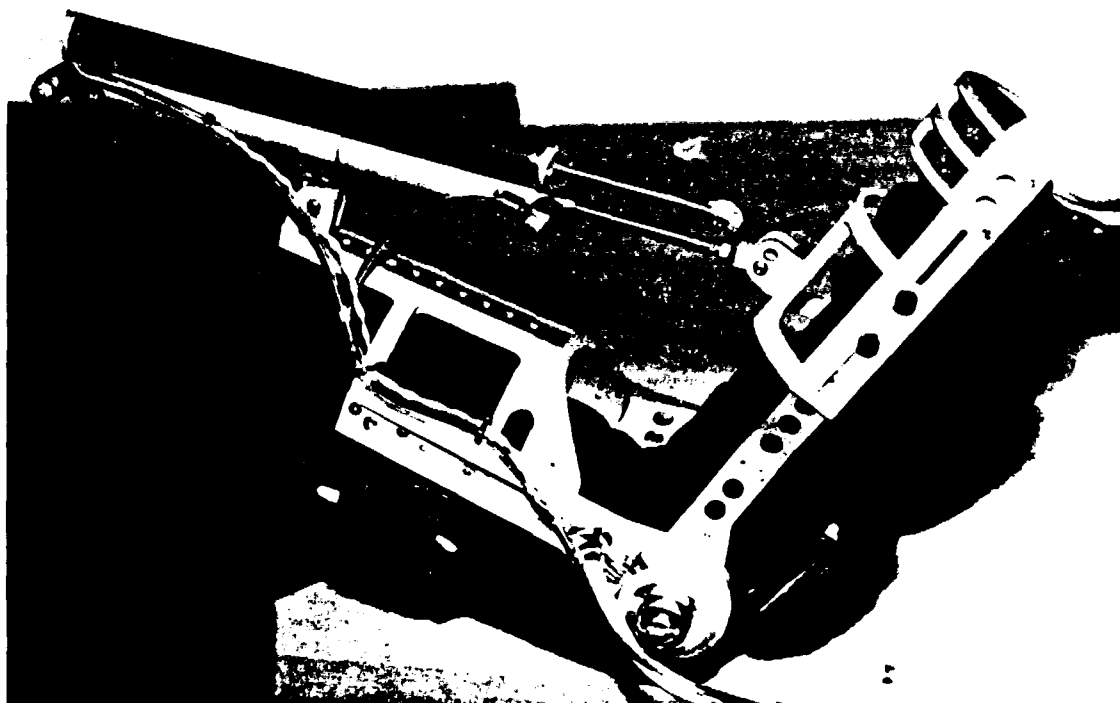
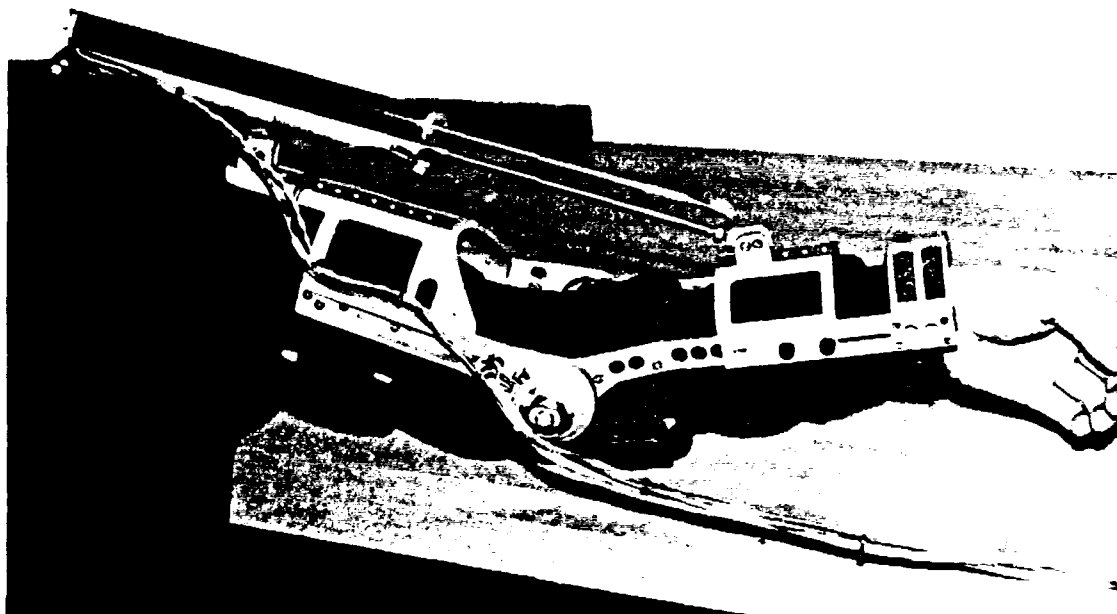


Figure 3. Orthosis positional geometry

Above: Near maximum extension (approximately 20 degrees)

Below: Approaching maximum flexion (approximately 80 degrees)



angle, θ , showing the orthosis near maximum extension and then approaching the 93-degree maximum flexion angle.

To find the smallest cylinder possible that would give us this range of motion, the distances between the adjustable cylinder mounting bracket locations had to be measured when the arm was at both maximum extension and at maximum flexion. We found that with the mounting brackets in their closest position toward the elbow joint we could achieve an acceptable range of motion with a cylinder having eight inches of stroke. The reason the smallest possible cylinder is necessary is not only for aesthetic quality but because if it were too long the rear part may contact the patient's shoulder.

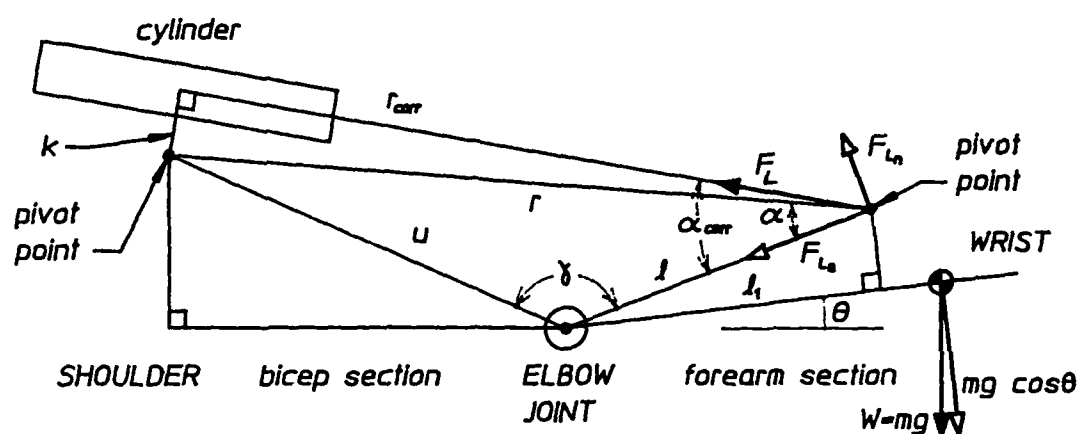
The next consideration for sizing the cylinder was determining how much force it would be required to transmit given a constant supply pressure. The variable here is cylinder bore, or diameter, which directly relates to piston area and therefore force output (force equals pressure times piston area). The following analysis determines F_L , the load force which must be applied by the piston to hold the arm in static equilibrium against gravity. Since the arm will be commanded to operate through a motion profile which requires a constant velocity and no acceleration, inertial forces can be ignored. Once the maximum force is calculated, the proper cylinder can then be selected.

Referring to the free-body diagram of Figure 4, in equilibrium the sum of the moments about the elbow joint is zero:

$$\ell F_L \sin \alpha_{\text{corr}} = \ell_1 mg \cos \theta$$

from which we find:

Figure 4. Orthosis diagram showing variables used in calculations



F_{L_n} = load force component normal to l

F_{L_p} = load force component parallel to l

F_L = cylinder load force

l = distance from elbow joint to forearm pivot

l_1 = distance from elbow joint to forearm center of gravity

u = distance from elbow joint to bicep pivot

r = distance from bicep pivot to forearm pivot

r_{corr} = corrected distance from cylinder mounting bracket to forearm pivot

k = height of cylinder centerline above bicep pivot

θ = rotation angle of forearm relative to horizontal

m = combined mass of orthosis forearm section and patient forearm

$$F_L = \frac{\ell_1 mg \cos \theta}{\ell \sin \alpha_{corr}}$$

It can be seen that the maximum load force will occur when $\theta = 0^\circ$ (when the arm is at full extension) because here α (and thus $\sin \alpha$) will be its smallest value and $\cos \theta$ will be at its greatest. The variables ℓ , m , and ℓ_1 are all measurable which leaves the problem of determining α .

From the law of sines,

$$\frac{r}{\sin \gamma} = \frac{u}{\sin \alpha}$$

so

$$\alpha = \arcsin\left(\frac{u \sin \gamma}{r}\right)$$

and

$$\alpha_{min} = \arcsin\left(\frac{u \sin \gamma_{max}}{r_{max}}\right).$$

We can find γ_{max} from the law of cosines (r_{max} is measurable)

$$\gamma_{max} = \arccos\left(\frac{\ell^2 + u^2 - r_{max}^2}{2\ell u}\right)$$

Using values measured from the orthosis and taken from CAD drawings

$$r_{max} = 15.94 \text{ inches}$$

$$\ell = 7.026 \text{ inches}$$

$$u = 9.747 \text{ inches}$$

we calculate that $\alpha_{min} = 21.47$ degrees.

Correcting for the fact that the bicep section's cylinder mounting collar raises the centerline of the cylinder a height k above the pivot point (Figure 4),

$$r_{corr} = (r_{max}^2 - k^2)^{1/2}$$

and

$$\alpha_{corr} = \alpha + \arcsin\left(\frac{k}{r_{corr}}\right).$$

With k measured as 1.05 inches, we get $\alpha_{corr} = 25.26$ degrees.

The orthosis forearm section weighs approximately 0.75 lb, and a volume displacement test performed on my forearm showed its weight to be about 3.0 lbs (or about 1.9% of my body weight, assuming arm density of 1.053 g/cm³). Adding a few pounds to these values to account for the maximum expected forearm weight for a large person and to provide for growth to the orthosis, I chose 6.0 lbs as the maximum weight the cylinder would have to lift. This weight acts at a distance ℓ_1 (center of gravity location) from the elbow joint which was determined for the orthosis forearm section by a basic "knife edge" balance test with the adjustable forearm extender in the furthest position. It was then assumed that for our maximum expected patient forearm size the center of gravity location would be no further than 10 inches from the elbow joint, giving us the worst case distance for the orthosis/patient arm center of gravity location. With that,

$$F_L = \frac{(10 \text{ inches}) (6 \text{ lbs}) \cos 0^\circ}{(7.026 \text{ inches}) (\sin 25.26^\circ)} = 20 \text{ lbs}$$

To ensure enough force would be available to provide a stiff, responsive system even at worst-case conditions and to overcome frictional forces, we decided that the pneumatic cylinder should have a force output capability of about 40 pounds at a supply pressure of 80 p.s.i. (pounds per square inch). Most cylinders are rated for slightly different force outputs on the extension and retraction strokes due to the small area lost to the piston rod. Since we would require the highest force moving the orthosis from maximum extension to maximum flexion (because of gravity) which is the direction powered by this smaller area of the piston in our particular configuration, we chose a cylinder which provides about 40 pounds in that direction (and obviously provides slightly more in the opposite direction due to the full area available on the piston). The cylinder we are using has a bore size of 0.75 inch. At this point in the development of the mechanical system the possible effects of muscle spasticity on the required force output of the cylinder were not taken into consideration. A cylinder with a larger bore could easily be substituted to provide more force if necessary.

Early in the design of the robotic arm we assumed incorrectly that the patient's arm should be exercised using a sinusoidal velocity profile, providing a slightly higher speed in the middle of the range of motion than at both extremes. For this reason analyses were accomplished to find the velocity and

acceleration of the orthosis through its arc for use in load force calculations and determination of mechanical time constants. Per Dr. Lieber's suggestion, the orthosis is now commanded to move only at constant velocities, which eliminates the need to present those analyses in this report. They are on file with Dr. Schneider for reference.

B. CONTROL SYSTEM

Because there exists the requirement to maintain the orthosis precisely along a path or at a position commanded by the user-defined motion profile, a closed-loop feedback control system was necessary to measure actual arm position and compare that with the commanded arm position then perform any corrections resulting from their difference.

Since the power transmission medium is a fluid in our case, the control of the system is more complicated due to the compressibility of the air. Only in the past ten years or so has the technology become available to provide precise positioning control of pneumatic systems. The availability of high-speed controlling electronics and pneumatic servovalves allows the closed-loop control of a system by quickly and continuously restoring equilibrium across the piston in the power cylinder should it change from its commanded value [4]. The term servovalve merely refers to the fact that the valve's output or response is directly proportional to its input signal from feedback sensors which may be constantly varying in order to bring the system to its commanded position, velocity, etc. [5]

In fact, closed-loop control provides automatic compensation for changes in command signals, friction, temperature, transient loading, and leakage.

A basic closed-loop position control system is shown in Figure 5. Our robotic orthosis uses this configuration as well as several other devices for sensing and control which will be discussed later. From the figure we see that the servo control amplifier produces an error signal which is the difference between the command signal (a voltage representing the desired position) and the feedback signal (also proportional to position). This error signal will cause the servovalve to displace its inner spool (see Figure 6) enough to bring the pressure in the cylinder to a point where the piston moves and the feedback device reads exactly the same voltage as the command signal. When this occurs, the error signal becomes zero and the orthosis, attached to the piston, is now static until the command signal changes.

The servo control amplifier is a commercial circuit board which not only accepts the command signal and feedback inputs and produces the servovalve driving signal, but also contains potentiometers for adjustment of the gains for the feedback and error signals (among others). This provides the proportional control which improves system performance.

Using a 5 k Ω linear potentiometer (which is mounted above the pneumatic cylinder) to generate a voltage proportional to the piston rod position and inputting this signal to the servo control amplifier, we found that the motion of the orthosis under a sinusoidal command signal was slightly jerky. Mr. Richard

Figure 5. Basic closed-loop position control system

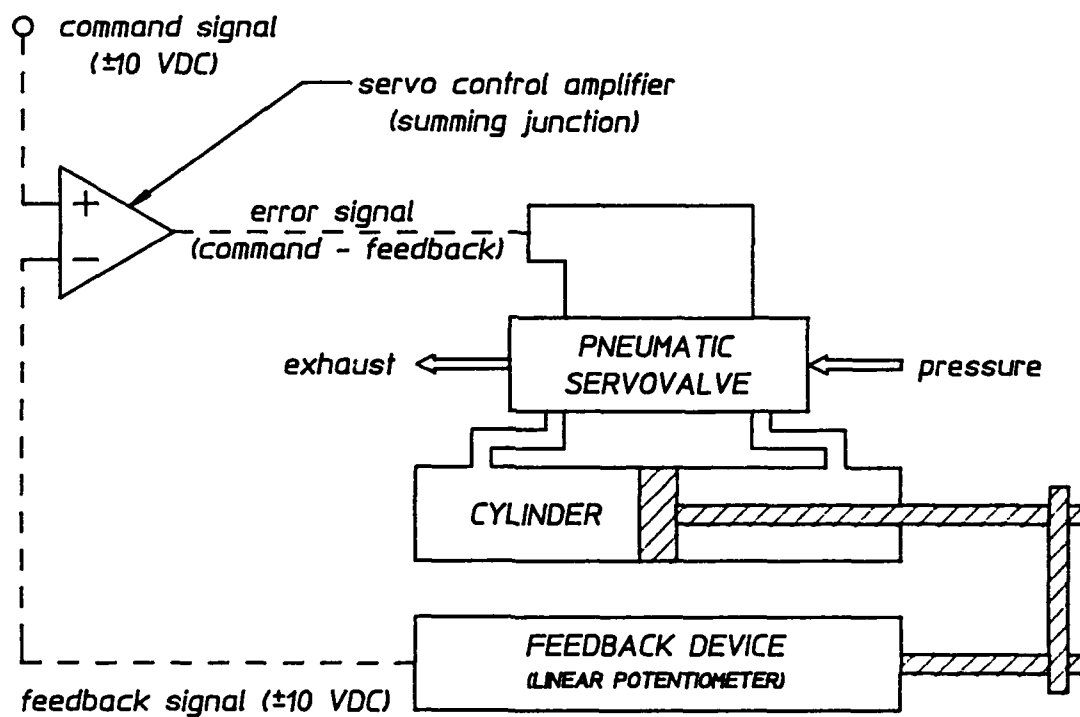
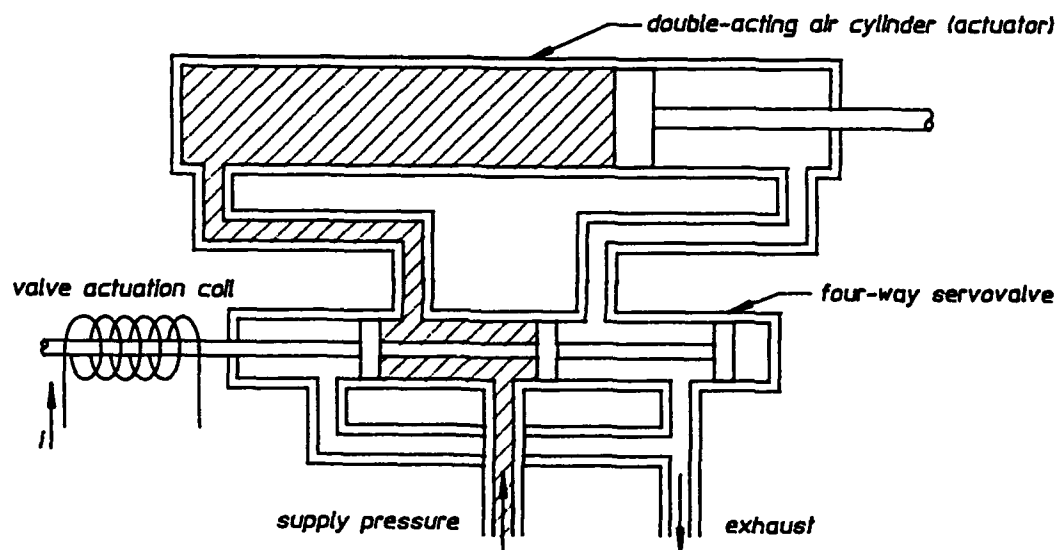


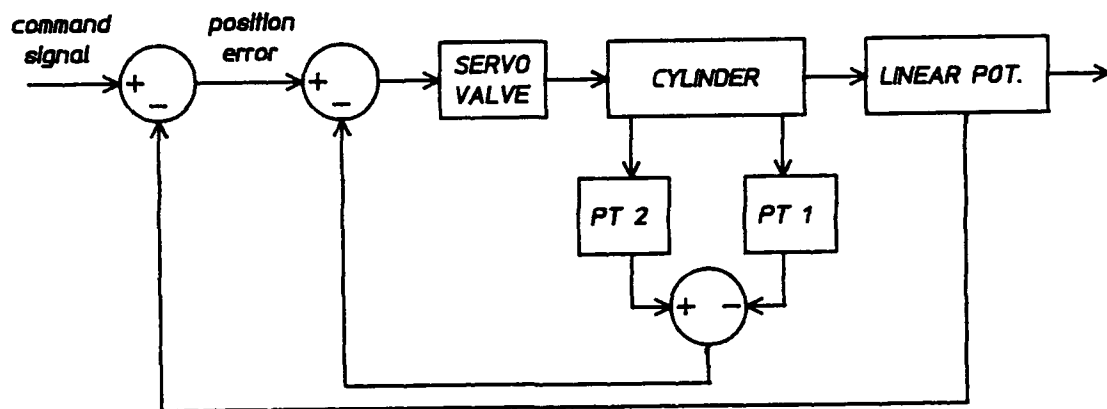
Figure 6. Schematic of four-way servovalve and air cylinder



Duder of Dynamic Valves, Inc. [6], the company from which the servovalve and servo control amplifier were purchased, suggested that improvements in control loop stability could be achieved by using a dual closed-loop configuration with pressure feedback as the inner loop and position feedback as the outer loop, as in Figure 7. This is true because with position feedback only, the error signal causes the servovalve to output a linear flow rate which in turn moves the orthosis at a proportional velocity. However, if the position error is used as the input signal to a pressure feedback loop, the output of the servovalve will generate a force proportional to the signal that will drive the position error to zero. Laboratory tests under both conditions confirmed that using both pressure and position feedback provided a smoother, more stable orthosis movement.

Pressure feedback was introduced by using two pressure transducers which were connected in-line with the air hoses coming from both outputs of the servovalve and going to both chambers of the pneumatic cylinder. These transducers are designed to output 0 to 5 VDC when subjected to pressures of between 0 and 120 psi. Since we are only using a maximum pressure of about 85 psi, the maximum output signal from the units is only about 3 VDC. For this reason the FEEDBACK GAIN potentiometer on the servo control amplifier board was adjusted to amplify this signal so that it ranges between 0 and 10 VDC, matching the command input signal. The transducers were wired so that one produced a positive output voltage while the other produced an equivalent negative output voltage when connected to the compressed air supply. This was

Figure 7. Block diagram of position and pressure feedback control

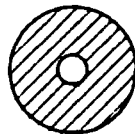
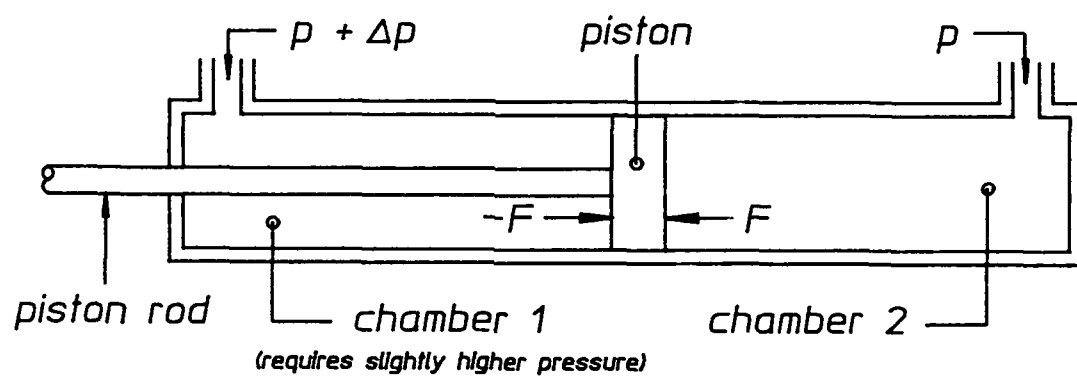


necessary because each output was connected to one of two feedback input terminals on the servo control amplifier, the sum of which was produced and used as the inner control loop feedback signal. In effect, we were using the circuitry available on the servo control amplifier board to create a differential pressure measurement since we did not have available such a transducer. The important concept is that the difference in pressure between both chambers in the pneumatic cylinder is a measurement of the force balance on the piston, and depending on the size of the load the piston is required to move, whether the piston is in motion (note that an equal force balance across the piston will require slightly different pressures in both cylinder chambers due to the smaller piston area where the piston rod is connected—see Figure 8).

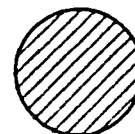
Because the addition of pressure feedback as the inner control loop required the two available feedback inputs on the servo control amplifier board, a separate summing amplifier was necessary to add the motion profile command signal with the linear potentiometer position feedback signal. This outer control loop creates the position error signal used as input to the inner pressure control loop. The summing amplifier circuit, shown in Figure 9, uses a standard integrated circuit operational amplifier.

Although another sensor, the optical rotary encoder mounted on the orthosis elbow, was available for use in the control system it was not incorporated into the analog servo amplifier circuit because of its inherent digital output. Its use will be described in Section V, Digital Computer Interface.

Figure 8. Pneumatic cylinder showing unequal chamber pressures but equal force

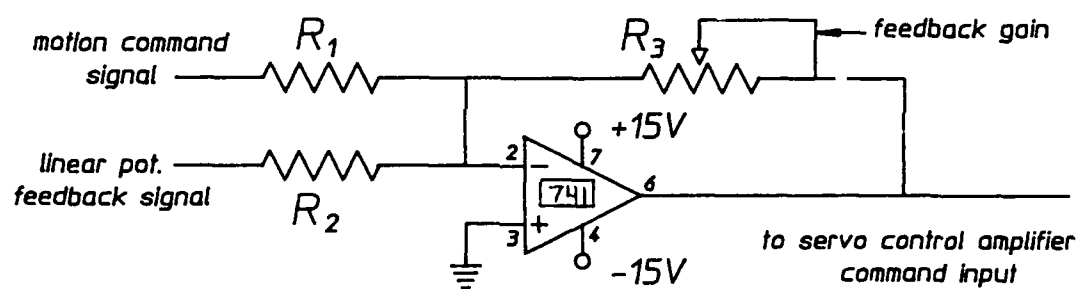


chamber 1 piston
effective area



chamber 2 piston
effective area

Figure 9. Summing amplifier circuit for position control loop
(Outer Loop Summing Amplifier, OLSA)



$R_1 = R_2$ for equal signal weighting

R_3 adjusted so gain=1 for frequency response testing ($R_1 = R_2 = R_3$)

In order to tune the control system so that the orthosis would respond to different inputs (i.e., impulse, step) in an acceptable manner, the amplifier gain values had to be properly adjusted. The outer loop summing amplifier gain was set to 1 so that system stability could be solely adjusted by the ERROR GAIN potentiometer found on the servo control amplifier circuit board. [NOTE: A procedure for matching magnitudes of the feedback signals and command signals on the servo control amplifier board must first be performed per the operations manual [7]. This is done to ensure the maximum feedback signal with gain (from the pressure transducers) is equal in magnitude but opposite in polarity to the maximum command signal (from the outer loop summing amplifier)]. With no command signal input provided to the outer loop summing amplifier, the system moves the orthosis to a position which generates zero volts from the linear potentiometer. Since the linear potentiometer is powered with +10 VDC at one end and -10 VDC at the other, its center position will produce an output of zero volts (an orthosis angle of about 45 degrees).

Movement of the arm by brute force while it is being held static generates a voltage from the linear potentiometer proportional to the displacement. Since there is no command signal present (0 volts), the output of the outer loop summing amplifier is equal to but opposite in polarity from this linear displacement signal and is sent to the inner pressure control loop. The servovalve immediately responds by increasing the pressure in the respective cylinder chamber to force the piston back to the center position. An impulse response was

simulated by forcing the arm away from its neutral central position and releasing. An oscillatory time response was observed initially. Adjusting the ERROR GAIN potentiometer on the servo board, the time response to this impulse input was optimized so that oscillations were eliminated but not at the expense of introducing too much damping (thus creating too slow of a response). To verify acceptable response to a step input, a constant voltage was applied to the outer loop summing amplifier command input. The system responded quickly and properly by positioning the orthosis at an angle which produced an equal but opposite voltage from the linear potentiometer with no visible oscillations.

With the control system configured as described above, the proposed exercise mode of the robotic orthosis is now basically functional. This mode merely requires a user-defined motion profile to be input as the command signal to the outer loop summing amplifier. The arm will move accordingly and can thus be used as a continuous passive motion device. A ± 10 VDC sinusoidal input was initially used to move the arm in this mode, but later a computer program was developed that can command the arm to move through any programmed motion profile.

This control system configuration also directly supports operation of the static evaluation mode in which the arm is held at a specified position and the patient uses his/her strength to try to move the arm. With a constant voltage command signal applied at the outer loop summing amplifier, the linear pot will hold the arm in a specified position within its range of motion. Any attempt to

displace the arm from this position will create an error signal from the position control loop and cause the servovalve to increase pressure in the appropriate cylinder chamber to maintain the commanded position. This pressure change can be measured at Test Point B on the servo control amplifier circuit board [7]. This signal, therefore, has a direct correlation to the force input to displace the arm, and thus is a measure of the patient's strength. This relationship has not yet been quantitatively defined. Calibration using a load cell has been suggested as one method of determining this force to verify it has a linear relationship with the pressure change across the cylinder piston.

It has also been suggested that measurement of a stroke patient's bicep muscle spasticity would be useful. Laboratory experiments show that while the arm is in the passive exercise mode described earlier that any resistance encountered along the arm's trajectory will create a corresponding pressure increase in order to overcome and maintain the commanded position. This in turn creates a voltage signal that can be used in the measurement of the magnitude of spasticity. Difficulties that may be encountered with this measurement, however, include any volitional, or desired, muscle activity by the patient which may taint the spasticity measurement.

Some preliminary analysis has been performed by Dr. Schneider to determine the proper control system configuration necessary for the "percent assist" mode of orthosis operation. Here the pneumatic cylinder is preloaded

with a selected fraction of the force required to place the arm in motion and therefore may require pressure feedback only in order to operate properly.

IV. SYSTEM TESTING AND ANALYSIS

With the control system configured as described in the previous section such that the arm follows a commanded motion profile (passive exercise mode), the system transfer function was characterized by performing various frequency response tests using a sinusoidal signal with known magnitude and frequency applied to the outer loop summing amplifier. The voltage signal from the linear potentiometer was measured as the arm oscillated through its range of motion, then the frequency of the sine wave was increased. This process continued until the arm was oscillating so fast and its amplitude was attenuated by so much that it appeared to be at rest. These data were used to create a frequency response, or Bode, plot of the system. From this plot, approximations to the actual system transfer functions can be made. Once transfer functions are available, standard control system analysis techniques can be used to design any required compensation into the system to make it perform in a specified manner. The following test data and analyses are relevant only at a supply air pressure of 80 psi and with the amplifier gains set at the values discussed later in this section.

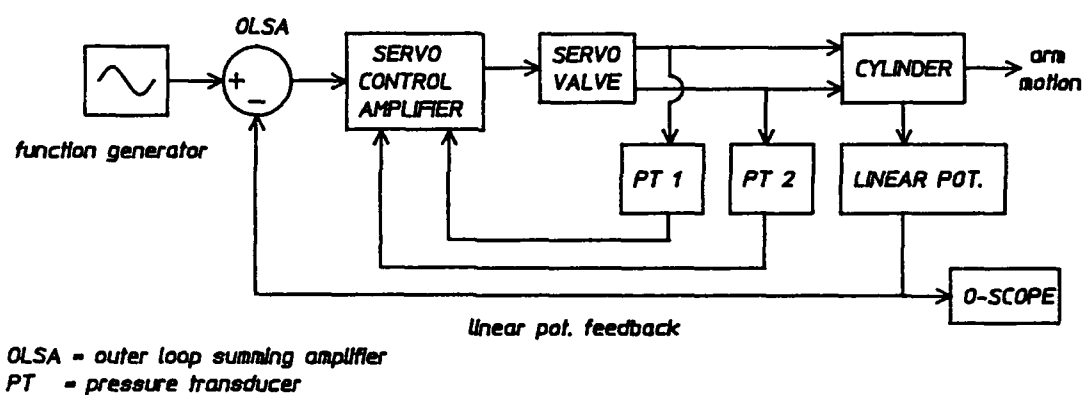
A Hewlett-Packard Model 3312A Function Generator was used to provide the sinusoidal command input. The sine wave output amplitude was adjusted initially using a digital multimeter to span a range of +10 VDC to -10 VDC, thus matching the linear potentiometer's output range. Once this signal was input to the outer loop summing amplifier however, it was causing the orthosis to strike its mechanical stops (cylinder piston extreme points). This was due to

the fact that the linear potentiometer output was actually somewhat less than ± 10 VDC due to inaccuracies of the voltage-dropping resistors placed in-line with it (to drop the ± 15 VDC power supply voltage from the servo control amplifier circuit down to the desired ± 10 VDC). This problem was overcome by simply reducing the sine wave magnitude from the signal generator until a shorter range of motion was achieved. The output of the function generator was input to a Hewlett-Packard Model 54500A 100 MHz Digital Oscilloscope so that its amplitude and frequency could be easily determined after any adjustments.

CLOSED-LOOP TEST

The output of interest for the closed-loop system test is from the linear potentiometer (See Figure 10). This signal must still be connected to the outer loop summing amplifier to ensure closed-loop operation, so a probe was used to pick off this signal and send it to the other available oscilloscope input channel. Once the function generator was started, both signals were available on the scope. The test was initiated using a very low frequency (0.01 Hz) then a manual sweep of increasing frequencies was performed. At each selected input frequency, the magnitude of the output oscillation was measured from the linear potentiometer signal. As the frequency increased past 1.3 Hz, it was evident that the output was being attenuated relative to the input. Finally, at 9.0 Hz, the output was so attenuated that the magnitude was indiscernible on the oscilloscope. Graphical display of these data is available in the form of a Bode plot that can be found in

Figure 10. Closed-loop frequency response test configuration



Appendix A-1. The vertical axis of the plot depicts the magnitude of the ratio of the output voltage to the input voltage in decibels (dB), or

$$20 \log_{10} \left(\frac{\text{output voltage}}{\text{input voltage}} \right) .$$

From the plot we see (using the asymptotic approximations for the actual test data) that our closed-loop control system behaves as a third-order system because of the first-order (-20 dB/decade) attenuation slope at frequencies higher than about 1.3 Hz (8.17 radians/sec) and the second-order (-40 dB/decade) attenuation after about 3.0 Hz (18.85 rad/sec). The closed-loop transfer function (CLTF) could then be approximated as (assuming a damping factor of 0.5)

$$CLTF = \frac{1}{\left(\frac{s}{8.17} + 1 \right) \left[\left(\frac{s}{18.85} \right)^2 + \frac{s}{18.85} + 1 \right]}$$

or simplified as

$$CLTF = \frac{2902.85}{(s + 8.17) (s^2 + 18.85s + 355.32)} .$$

Since the arm will be operated at frequencies in the range of approximately 0.05 Hz to 0.3 Hz, our analysis shows that the bandwidth of the system is more than adequate (the output of the system will exactly match the input) and therefore no compensation is required. This experimentally derived closed-loop

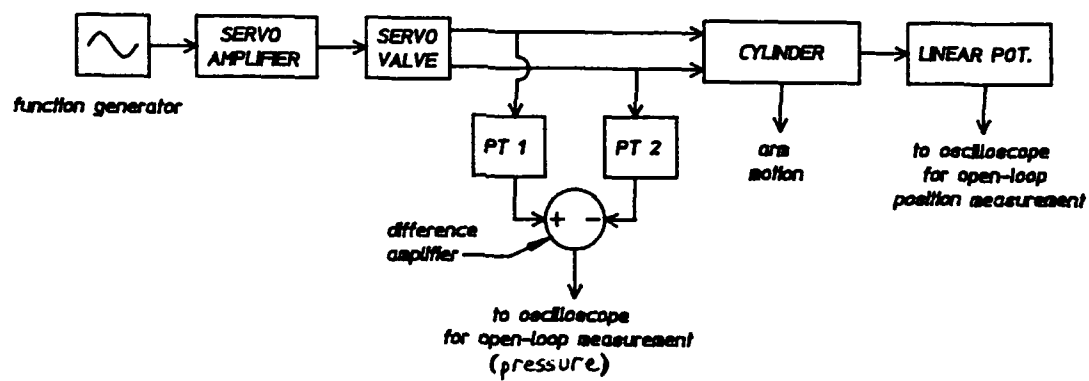
transfer function will be compared to an analytically derived model (using open-loop test data) at the conclusion of this section.

OPEN LOOP TESTS

More useful information can often be gained from open-loop frequency response testing than from closed-loop tests. An open-loop test can help us determine the actual transfer functions of any number of individual components or groups of components within the system. Once characteristics of the open-loop system are known (i.e., the location of poles and zeroes), the methods of classical control theory can be applied to dictate the desired system characteristics once the loop is closed. A closed-loop frequency response on the other hand merely displays how a complex system is responding with feedback under a given, static set of conditions.

Two separate open-loop frequency tests were performed; one in which the output of the pressure transducers was measured and the other in which the output of the linear potentiometer was measured. For both tests, the feedback loops from the pressure transducers and the linear potentiometer were opened (See Figure 11). The lack of position control made the performance of the frequency response tests very difficult as the center point for the arm's range of motion tended to drift. Since unmeaningful data would result if the arm reached the mechanical stop at either extreme position, I had to constantly adjust the amplitude of the input sine wave (using the vernier control on the function

Figure 11. Open-loop frequency response test configuration



generator) to try to keep the arm oscillating in an acceptable arc long enough to read a valid output magnitude signal.

In order to use the output from both pressure transducers now that they are disconnected from the servo control amplifier circuit board's feedback inputs, a summing amplifier was required to add the two signals to again create a single differential pressure signal (remember, the pressure transducers are wired so that they produce signals opposite in polarity to each other). The outer loop summing amplifier was used since it was not required for these open loop tests.

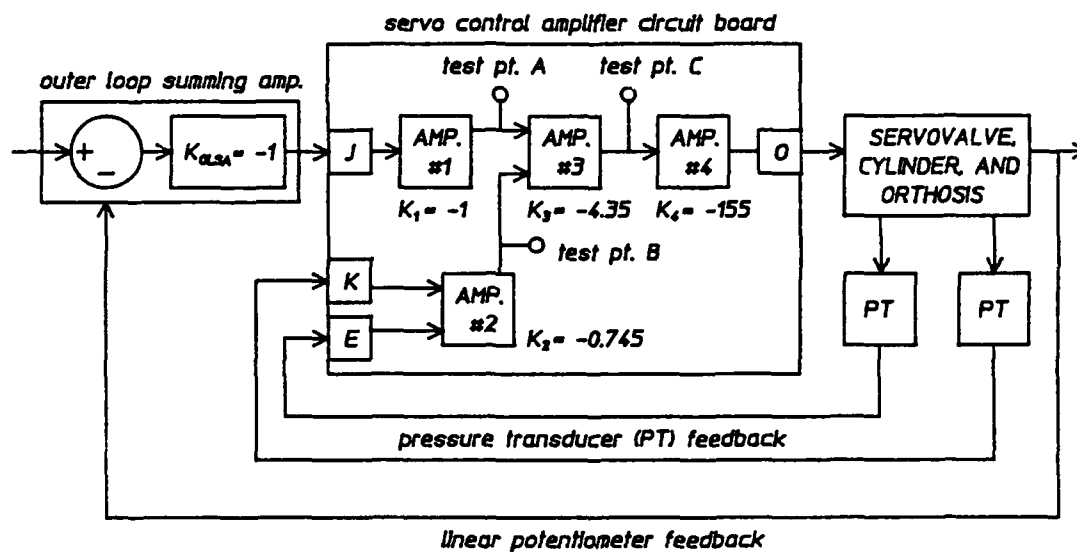
A procedure similar to that for the closed-loop test was used for performing the frequency response test of the open-loop system. The function generator was started and the appropriate output response signal from the control system (position or pressure) was measured and compared to the input signal magnitude. The frequency was increased from as low as practical to as high as output magnitude measurements were still discernible. See Appendix A-2 and A-3 for the Bode plots of these open-loop tests. It should be noted that these experimental measurements are by no means absolute; each time the test was performed slightly different values resulted. These Bode plots reflect the experience of several test runs each and are what I consider to be the most accurate data. During these tests, I also monitored the input-output phase relationship on the oscilloscope at each measurement. The resulting waveform (when the scope is placed in the "X-Y" display mode) is known as a Lissajous pattern and gives a qualitative measure of the phase lag of the output versus the

input signal. According to Ogata [8], experimental phase measurements are not as reliable as magnitude measurements due to their sensitivity to slight changes in system parameters and to system non-linearities. However, they can be used to gain some insight into the complexity of the system. Rough sketches of the Lissajous patterns as seen on the oscilloscope screen are available with the raw test data on file with Dr. Schneider.

In order to perform a meaningful analysis from these Bode plots, any amplifiers in series with the components whose transfer functions are sought must have their gain values known. These gains can then be removed from the measured open-loop transfer function to reveal the component's true gain value. This gain measurement test was performed using a Hewlett-Packard Model 6235A Triple Output Power Supply that supplied a constant voltage which I chose arbitrarily to be +3.0 VDC. This voltage was applied to the various amplifiers in our system, including the custom open loop summing amplifier and the various amplifiers on the servo control amplifier circuit board. Figure 12 shows these gain values as they appear in the system block diagram. It is important to note that the experimental frequency response measurements are based on these values of amplifier gain that were chosen to optimize system response to inputs as mentioned earlier. Any change to these values by adjusting the appropriate potentiometers will alter the frequency response test output.

It is now possible to use the Bode plots to again perform system characterization, the determination of a system's transfer function from

Figure 12. Gain values for system amplifiers



* gain values are negative because of inverting amplifiers

* K_{OLSA} , K_1 , K_2 , K_3 , K_4 in volts/volt

experimental response data. First we will use the output of the open-loop position measurement test found in Appendix A-2. It should be mentioned that the asymptotes drawn on the Bode plot (which must be multiples of ± 20 decibels per decade) are only visual approximations to actual test data. The asymptotic approximations I used show an initial first-order slope (an integrating effect of the servovalve with a constant voltage input signal creating a continuous, cumulative flow of air) with two other first-order breaks occurring at about 3.5 Hz (22 radians/sec) and 6 Hz (37.7 rad/sec). This reveals to us that the open-loop path for position control is third-order, as suggested by deSilva [5] and McCloy [9] for a pneumatic system similar to ours. The gain of the system is found by noting where the plot intersects a frequency of 1 rad/sec (0.16 Hz). In this case it is at 31.5 dB, or converting to natural numbers as a gain factor K ,

$$20 \log_{10} K = 31.5 \text{ dB}$$

$$K = 10^{\frac{31.5}{20}} = 37.58$$

Using the values in radians/sec for further calculations, the open-loop system transfer function (without pressure feedback) can be written as

$$OLTF_{\text{position}} = \frac{Y(s)}{X(s)} = \frac{37.58}{s \left(\frac{s}{22} + 1 \right) \left(\frac{s}{37.7} + 1 \right)}$$

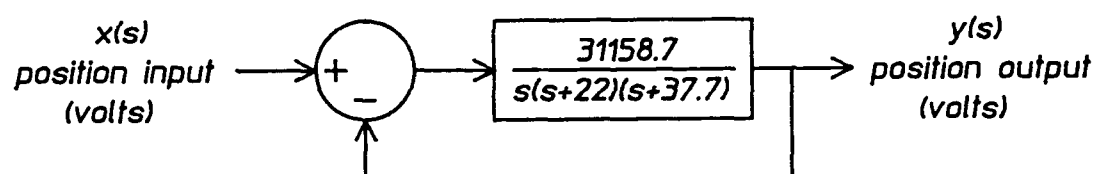
which when normalized yields

$$OLTF_{position} = \frac{Y(s)}{X(s)} = \frac{31158.68}{s(s+22)(s+37.7)}$$

where $Y(s)$ represents the Laplace transform of the output position from the linear potentiometer in volts and $X(s)$ the commanded input position in volts. This transfer function is a conglomeration of all system gains and dynamic characteristics in the open-loop forward path. A quick method for checking stability of this system when the position feedback loop is closed (assuming no pressure loop) is to perform a root locus analysis of the above transfer function. This is done in Appendix B-1 which shows that the closed-loop system with position feedback only is stable (the closed-loop poles are to the left of the vertical axis), although very little margin remains. In fact, the system can remain stable only if gain is increased by a factor less than 1.59. Figure 13 shows the block diagram for this system.

From the open-loop pressure measurement test Bode plot (Appendix A-3) we perform a similar analysis. Theory did not predict the very high gains measured at frequencies below 1 Hz, but this was most likely due to the very slow rate at which the servovalve was commanded to cycle back and forth thus allowing full air flow to the cylinder, in turn forcing the piston to its extreme position. Thus, if we neglect this portion of the Bode plot as not being inherent to the system dynamics, we simply find a flat response (constant gain of about -3 dB) with a first-order break at about 6 Hz (37.7 rad/sec), a very convenient

Figure 13. Block diagram of system with position feedback only



location keeping in mind this was also the location of a break frequency from the open-loop position measurement Bode plot. This constant gain of -3 dB converted to natural numbers gives

$$20\log_{10}K = -3\text{ dB}$$

$$K = 10^{\frac{-3}{20}} = 0.708$$

and a transfer function can now be written for this open-loop path as

$$OLTF_{pressure} = \frac{P(s)}{X(s)} = \frac{0.708}{\left(\frac{s}{37.7}\right) + 1}$$

which when normalized yields

$$OLTF_{pressure} = \frac{P(s)}{X(s)} = \frac{26.69}{s + 37.7}.$$

Knowing this transfer function helps us deduce the transfer functions and system dynamics of the individual components of the pneumatic/mechanical system. For example, we can see now from Figure 14 that the response of the orthosis is dependent on three distinct system characteristics; pneumatic lag, mechanical lag, and an integrating, or cumulative, effect.

Because the open-loop position and pressure tests both generated a first-order exponential decay term of

$$G_1(s) = \frac{1}{s+37.7}$$

we can consider this term the pneumatic time constant term

$$\tau_{pneumatic} = \frac{1}{37.7} = 0.027 \text{ seconds}$$

or the inherent delay in response due to the transmission of power via compressed air. The remaining first-order term would then be the mechanical lag, or delay, due to the inertial forces, friction, and other non-linearities integral to the mechanical arm

$$\tau_{mechanical} = \frac{1}{22} = 0.045 \text{ seconds}$$

and is almost double the delay of the pneumatics. Because we know the gain of the open-loop position transfer function to be 31,158.68, we can divide this value by the gain of the first first-order term found as the open-loop pressure transfer function (26.69) to find a gain value for the second first-order term within the system of 1,167.43 (shown in Figure 14).

Now that the individual contributions for each component of the system are known, we can close both the pressure feedback loop and the position feedback loop and analytically determine the effects of pressure feedback on the system response characteristics. The system block diagram is shown in Figure 15.

Figure 14. Breakdown of orthosis pneumatic/mechanical dynamics

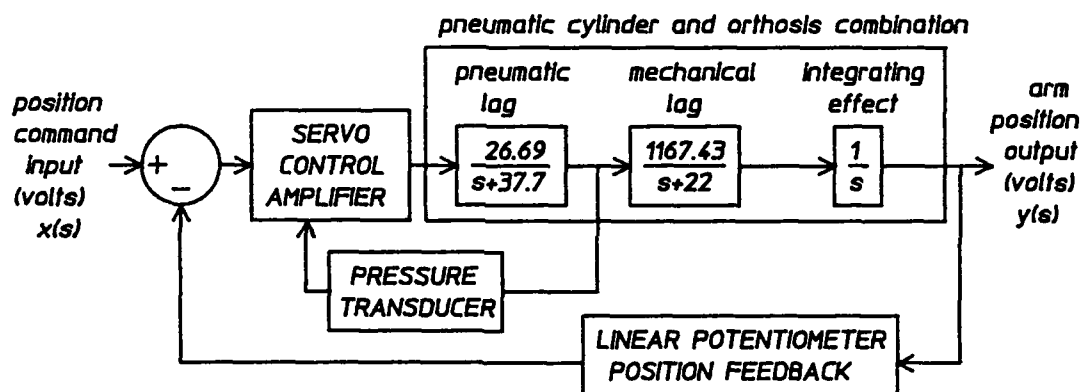
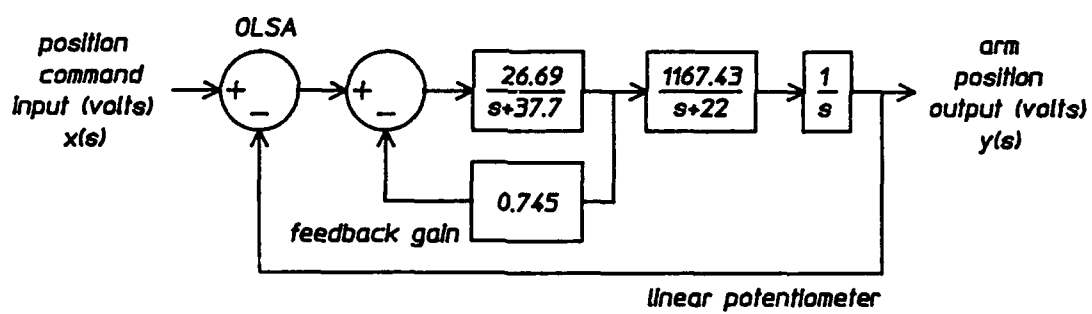


Figure 15. System block diagram



The inner feedback loop can be simplified by finding its closed-loop transfer function from

$$CLTF = \frac{G(s)}{1 + G(s)H(s)}$$

as

$$CLTF_{innerloop} = \frac{\frac{26.69}{s+37.7}}{1 + \frac{(26.69)(0.745)}{s+37.7}}$$

or simplified as

$$CLTF_{innerloop} = \frac{26.69}{s+57.58}$$

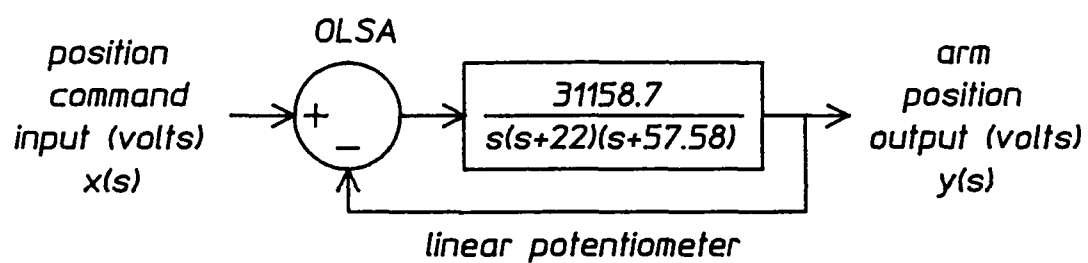
which when combined with the other components in the forward path yields the open-loop transfer function

$$G(s) = \frac{31158.68}{s(s+22)(s+57.58)}$$

and the simplified block diagram shown in Figure 16.

Referring to the block diagram of Figure 13, which does not take into account pressure feedback, we can see the similarity with this system containing both pressure and position feedback. A root locus analysis of the system transfer function which does include pressure feedback is given in Appendix B-2. This analysis reveals that the addition of pressure feedback to the system as the inner control loop has benefitted the system by increasing its relative stability (the system can now tolerate a gain multiplier of 3.24 versus only 1.59 without

Figure 16. Simplified system block diagram



pressure feedback). System damping was also affected positively by a slight increase in its value which helps control oscillations.

An interesting check can now be performed by comparing this semi-analytically derived closed-loop system transfer function (found from Figure 16 using unity feedback, or $H(s) = 1$)

$$CLTF = \frac{G(s)}{1 + G(s)H(s)} = \frac{31158.68}{(s+67.66)(s^2+11.92s+460.2)}$$

to the experimentally determined closed-loop system transfer function derived from the Bode plot in Appendix A-1,

$$CLTF = \frac{2902.85}{(s+8.17)(s^2+18.85s+355.32)}$$

Although there is an obvious discrepancy among the gains (a factor of 10.73) and the location of the real poles, the complex conjugate poles of both transfer functions are quite similar. Such errors may be due to test inconsistency, improper gain measurements, system non-linearities, and various other factors. The usefulness of this comparison as well may be limited.

With the system transfer function now available, it is possible to alter system response characteristics if desirable through implementation of proportional, integral, and/or derivative (PID) control algorithms. At the present this is not required because of acceptable system response but may be desirable to implement in the future.

Before this section is concluded, it should be mentioned that the dynamic characteristics of the servovalve and the pressure transducers were neglected in this section's frequency response analyses because of their high bandwidth. The servovalve has a rated bandwidth (frequency up to which the component's output replicates its input, or a flat frequency response) of 90 Hz and the pressure transducers are rated to about 100 Hz, both much higher than our system was required to respond (pressure transducer data was obtained from the manufacturer, Wiancko Engineering Co. of Tarzana, CA).

V. DIGITAL COMPUTER INTERFACE

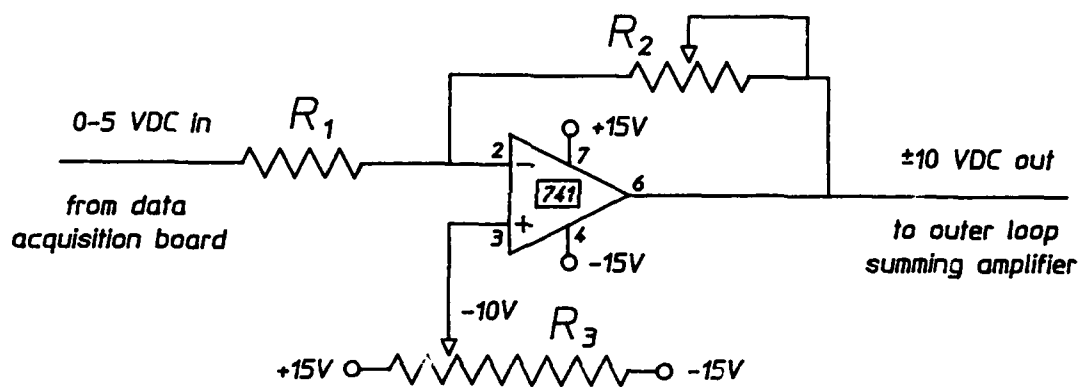
Once it was determined that the robotic orthosis system was properly responding to commanded inputs, transition over to digital control was desired. Using a computer as an interface between the operator and the controlling electronics is an advantage not only in that it makes the system more user-friendly through use of custom software, but also allows greater flexibility in providing control to the system. If the proper signals are provided to the computer, many complex algorithms may be developed to precisely dictate the response of the system to any input. Our system in its present state has been integrated with the computer but not to its full potential. Software has been written which generates a user-specified motion profile for the orthosis by taking position feedback from the optical encoder device on the elbow joint as input and outputting a voltage related to the desired arm position. Pressure transducer voltage signals have also been fed to the computer so that they may be used to assist in system control. The remainder of this section presents the detailed configuration of this computer hardware interface while detailed description of the software will be discussed in Appendix C.

Up to this point, we have described the robotic arm as controlled by an entirely analog, or continuous-time, control system made up of the outer loop summing amplifier and the servo control amplifier circuit board. Interfacing an analog system to a digital, or discrete-time, system requires the use of analog-to-digital (A/D) converters and digital-to-analog (D/A) converters. These are

present in our system in the form of a data acquisition circuit board which installs inside the computer, in our case a 286-based 12 MHz IBM clone. This Kiethley-Metrabyte DAS-16F data acquisition board has eight differential (signal source and signal common) analog inputs and two separate D/A-converted continuous signal outputs that can operate at sampling rates of up to 100 kHz. Control of the board is via special software commands [10] which can be incorporated into any programming language, but in our case it was most effective to use the BASIC language [11] since many supplied example programs were already written in BASIC.

The first requirement was to use the computer and data acquisition board to generate a command voltage that would be input to the outer loop summing amplifier. Since the linear potentiometer provides a feedback signal in the range of slightly less than ± 10 VDC, the command signal must be matched accordingly otherwise the arm will either move further or shorter than desired. Using a reference voltage source of -5 VDC available on the data acquisition board itself, the board can only produce an output signal in the range of 0 to +5 VDC. Therefore, a signal conditioning amplifier circuit that converts this 0 to 5 VDC signal to a ± 10 VDC signal was built. This was done by amplifying the data acquisition board signal by a gain of four to get a 0 to 20 VDC signal then offsetting this with a constant -10 VDC to achieve the required ± 10 VDC range (schematic shown in Figure 17). Potentiometers were used to provide the gain adjustment so a precisely determined signal could be achieved.

Figure 17. Data acquisition board output signal conditioning circuit



R_2 adjusted so that $R_2 = 4R_1$
 R_3 adjusted to achieve bias of -10 VDC

The method used by the data acquisition board to output a voltage is to convert a user-definable bit count stored in a data array of between 0 and 4095 to a proportional 0 to +4.9988 VDC output signal (using -5 VDC as reference input). This is important because all software control of output voltages must be performed in this fashion whereby the number of bits represents a proportional voltage. Any waveform such as a continuous DC voltage or a sinusoid can be output by the board by loading the appropriate software array with the proper bit values. For example, a constant voltage of +1.0 VDC from the board (equivalent to approximately -6.0 VDC once passed through the signal conditioning amplifier) would be generated by loading several elements of an array with an integer bit value of 819 (as calculated below)

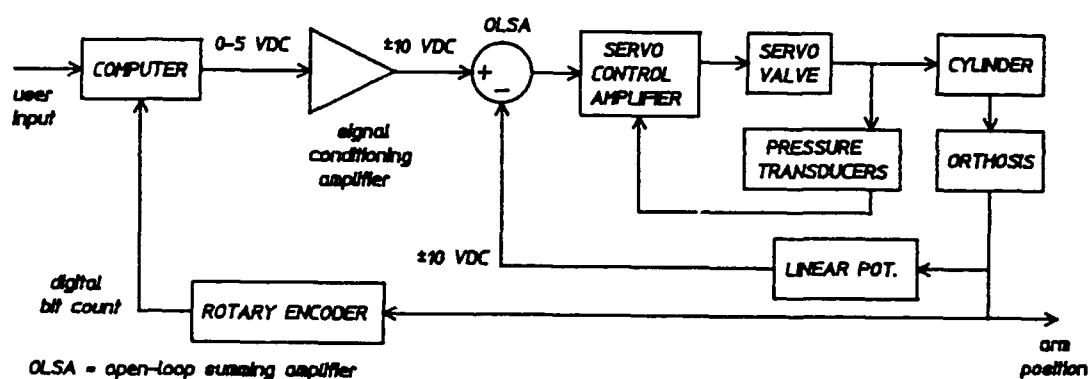
$$\frac{1.0 \text{ VDC}}{4.9988 \text{ VDC}} = \frac{x}{4095 \text{ bits}}$$

$$x=819.2$$

and commanding the software to continuously read this array and output the appropriate voltage. This method is used several times in the orthosis control software to bring the arm to or hold the arm at a specified angle.

The method of position feedback control at this point is still provided by the analog linear potentiometer signal being summed with the data acquisition board conditioned signal at the outer loop summing amplifier (see Figure 18). Hence, the computer is merely acting as a command signal generator. In order

Figure 18. System block diagram showing digital computer interface



to provide some computer control over arm position, the pulsed signal generated by the rotary encoder mounted on the orthosis elbow joint was sent to the computer via a special quadrature amplifier circuit board custom built by the department electronics technician. Although it would now be possible to use the encoder data as position feedback instead of the linear potentiometer feedback, time restrictions allowed me to use it merely to display the current angle of the arm. Nevertheless, it is still important to understand the operation of the encoder when interfaced with the computer as it has much greater potential with our system.

The optical rotary encoder consists of a disk with 1024 small slots evenly spaced around the circumference and infrared sensors which emit a pulse each time one of these slots passes. The quadrature amplifier circuitry can distinguish between pulses as well, so the actual resolution of the encoder is 2048 counts per revolution (360 degrees), or 0.176 degree per count. The counts are accumulated in a memory storage register so a precise value for the angular position of the arm can be calculated by multiplying the number of counts in the register by 0.176 degree (assuming the counter was initialized at the zero degree arm position by storing a value of zero at the initialization memory address, hex 304₁₆).

The memory storage location for the encoder counter register requires two bytes (eight bits per byte), allowing a bit count of up to 65,535 ($2^{16}-1$). The low byte alone allows a count of up to 255 (2^8-1), but since our arm will move through an angle of about 94 degrees, this requires a count of about 532, so the high byte

is also needed. The low byte is available at a hex address of 301_{16} while the high byte is found at hex address 300_{16} . Software commands as found in the orthosis control program (Appendix C-1) can be issued to read these values and use them to find the absolute arm angle. It is necessary to point out that the encoder increments as the arm is rotated in one direction and decrements when rotated in the other direction. If the encoder register is initialized with a zero count and the arm rotates in the direction that causes the encoder to decrement the count, erroneous data results (Appendix C-2 contains a simple program that shows the encoder register count only). This problem is encountered and corrected via software in the orthosis control program.

By using the data acquisition board's A/D conversion ability, we have demonstrated that the differential pressure signal available from the servo control amplifier circuit board (at Test Point B) can be sampled and therefore used in some manner to either aid in system control or measure any resistance the patient may be offering, voluntarily or involuntarily (i.e., muscle spasticity). This prospect has not been fully investigated at this point, but a strip chart example program supplied with the data acquisition board (QBSTRIP) has allowed us to graphically display variations in pressure as the arm is forced to move.

One final important note on hardware configuration is that the default base address setting for the data acquisition board inside the computer is 300_{16} (hex), the same address as the encoder register. Therefore, the data acquisition board's set switches had to be changed to represent a new memory address that did not

conflict with the encoder or any other intrinsic computer functions (we chose hex address $2F0_{16}$). The INSTALL.EXE program provided with the board must be run to create a file containing the new address location for use by the board's own controlling software [10].

VI. SAFETY ENGINEERING

Safety of both the patient and the operator is a major concern with this pneumatically-controlled system. Compressed air even at the 80 pounds per square inch we are using can generate enough force to cause serious injury to body parts in the way of moving orthosis parts. Several safety measures have been incorporated into the orthosis hardware, but several more need to be added before we can justifiably expect a stroke patient to use it for the first time.

The stroke of the air cylinder itself determines the maximum extension and flexion angles, so the mechanical mounting of the cylinder on the arm provides the mechanism by which hyperextension of the patient's arm is avoided. This will be considered the "mechanical stops" as mentioned early in this report. With maximum rotation angles controlled, the next obvious safety concern is that the rate at which the arm rotates be controlled. Although the orthosis control program generates a comfortable motion profile as specified by the operator, should a failure occur either in the software or in the electronic circuitry that causes the servovalve to pass full flow to the cylinder, a mechanism must be in place to keep the rotation speed to one that will not injure the patient. Pneumatic speed control valves were placed at the cylinder ports through which the flow of air is limited according to orifice size (adjustable by thumbscrew). These speed control valves can be set to keep the maximum rotation speed down to a safe level, but should not restrict the air flow too greatly otherwise the system will be overdamped and may not operate properly at normal rotation speeds.

(NOTE: These speed control valves were not installed during frequency response testing, allowing free flow of air to the cylinder).

The orthosis control software incorporates some concern for safety but this endeavor needs to be expanded. At the start of the program when the arm must swing from one extreme point to the other, the software displays a red warning screen and waits for a key press from the operator to ensure nobody is near (or strapped in). Also, during operation of the arm, the operator is reminded that at any time any key on the keyboard may be pressed to stop motion if required.

VII. IDEAS FOR FURTHER IMPROVEMENT

This section lists both suggestions that should be incorporated as soon as practical and ideas which may in the future contribute to the efficient operation of the system. They are broken down into four categories: Hardware modifications, control system challenges, software improvements, and safety additions.

HARDWARE

1. An effective mounting platform needs to be developed that will easily allow the operator to fasten the orthosis to the patient in the wheelchair (in work).
2. The cylinder mounting position should be altered so as to move the available 94 degree range of motion from a starting angle of 0 degrees to one of about 25 to 30 degrees so that the maximum flexion angle becomes about 120 degrees or 130 degrees (suggested by Dr. Lieber--patient would then be moving arm at an angle that, once rehabilitated, allows easy access to the mouth area).
3. It should be fairly easy to disconnect the pneumatic cylinder from the orthosis and install a DC servomotor which can be controlled by the existing system components. This might provide useful information should this alternative be more desirable at a later date.
4. The incorporation of a mechanism which attaches to the existing orthosis structure and provides wrist flexion and extension as the arm is operating

would be fairly easy to incorporate and could prove to be a great benefit in patient rehabilitation.

CONTROL SYSTEM

1. Operation of the "percent assist" mode may require temporary removal of position feedback from the system so that it operates under pressure control only. This can be done most efficiently by rewiring the linear potentiometer feedback from the outer loop summing amplifier to the data acquisition board (as an analog input to be digitally converted) where it would be summed with the software-generated command signal in normal operation or ignored while in this mode. The system should compensate if the patient were to add more force than necessary to put the orthosis in motion at the selected assist percentage (thus causing an acceleration and increase in velocity) by reducing the degree of assist in an attempt to maintain a constant arm velocity.
2. An improvement to the aesthetic appearance of the orthosis could be achieved by removing the linear potentiometer, which then dictates that the system would receive position feedback solely from the optical rotary encoder. This should be feasible with proper software development.
3. Addition of integral or derivative control techniques to improve system performance might be interesting. The servo control amplifier circuit board has provisions for such rate compensation.

4. Adjustment of the gain potentiometers throughout the circuitry may yield a better combination of system gains which could improve performance.

SOFTWARE

1. The user interface should be tested by several potential operators and their suggestions incorporated.
2. Programs written in BASIC should be compiled using a BASIC compiler or converted to another language to significantly increase processing speed.
3. A module should be written to take the sampled pressure transducer difference signal and use it to determine patient strength during the static evaluation mode or measure muscle spasticity during the passive exercise mode.
4. The existing orthosis control program should be upgraded to include the ability to perform the patient's initial range of motion calibration without pneumatic assistance. The therapist would move the orthosis/patient arm to a maximum desired extension angle then press a key to store that angle (available from the encoder register) and do the same for the maximum desired flexion angle. Pneumatic assistance could then be applied at this point.
5. Real time graphical display of selected parameters should be an option. Incorporate the example program "QBSTRIP" to get real-time display of pressure difference for use in the static evaluation mode.

6. A master control program should be developed that contains a patient database and stores information in files from all previous patient tests. It should also be able to graphically display a progress history and output relative quantitative values for study (i.e., strength, power, energy, etc.). It should also allow selection of the various test modes.
7. Code should be written to generate periodic interrupts (from the data acquisition board) at a preselected time interval which would fetch the value in the encoder register. Using algorithms currently being developed and tested, these periodic encoder counts can be used to determine angular velocity and acceleration of the arm which would then be used in the calculation of power and energy. These calculations will be required in the dynamic evaluation mode.

SAFETY

1. Areas on the orthosis which could crush the hand and/or fingers during operation should be covered with some sort of rubber, plastic or cloth boot. Such areas include the area directly above the elbow joint and underneath the piston rod mounting bracket.
2. In order to regulate supply pressure at a constant predetermined value, the electro-pneumatic regulator (donated by SMC Corporation) could be used and, in fact, controlled via computer if pressure changes were desired (i.e., to unstrap patient, to allow therapist to move orthosis/patient arm, etc.). Also, an electrically-operated bi-directional valve (also from SMC) could

be placed in the air circuit that would require a constant voltage for air to flow to the system so that any power failure or operator-initiated emergency stop sequence would protect the patient arm from sudden movements.

3. Any controlling software needs to be thoroughly tested to ensure certain actions or keystroke combinations do not result in the sudden, uncontrolled movement of the arm. The current version of the orthosis control program does have these problems under certain conditions when using the cursor positioning controls.

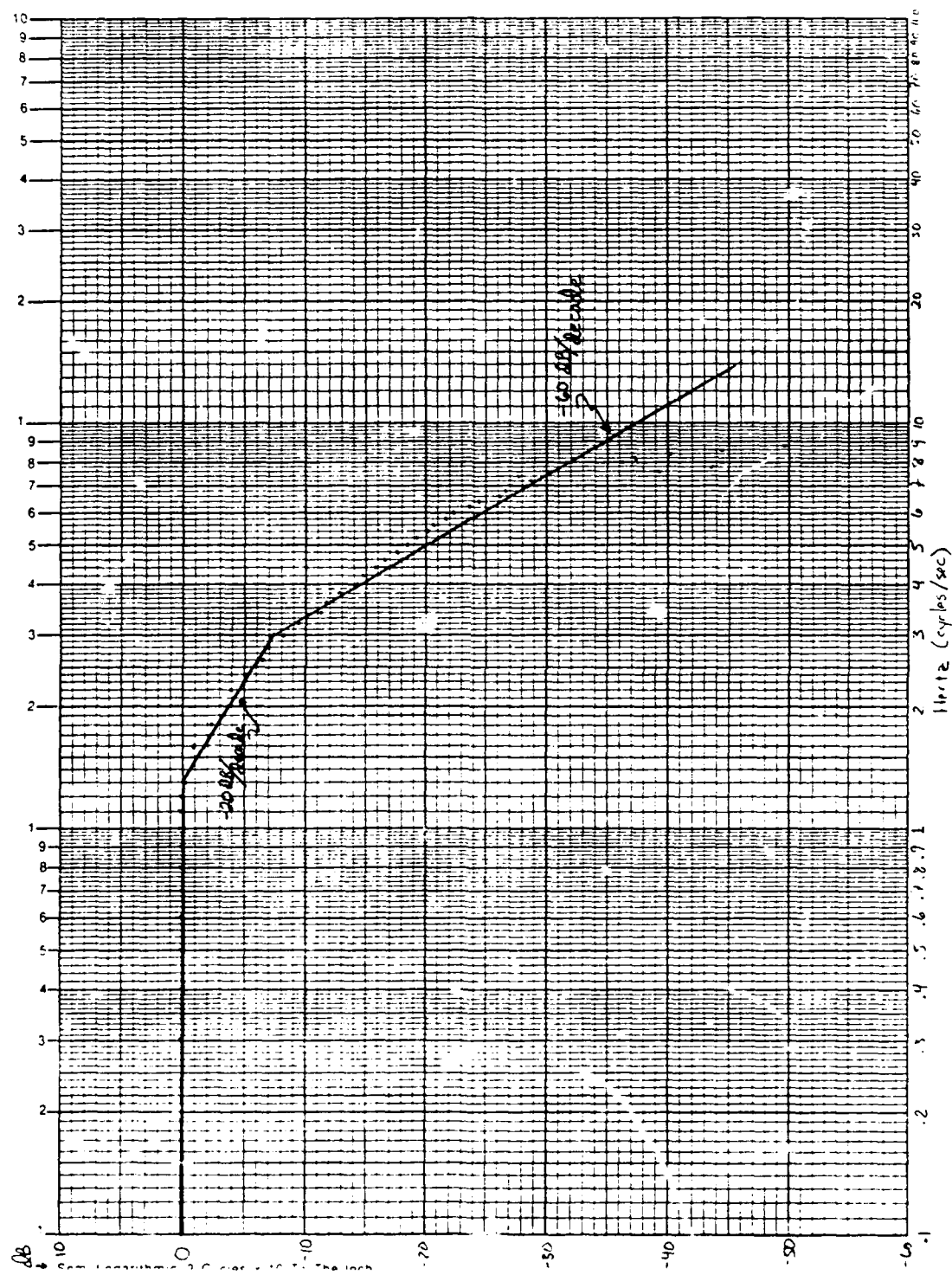
VIII. CONCLUSION

We have seen that pneumatics is a viable option for powering our orthosis by providing smooth, precise control of arm position and that our configuration has the capability to command the arm in several different modes of operation. Much work has been done to bring the robotic arm to this stage of development, but much more remains to continue developing ways in which it can be more useful to the people who will be operating it and hopefully more beneficial to the patients who may eventually use it as part of their rehabilitation program.

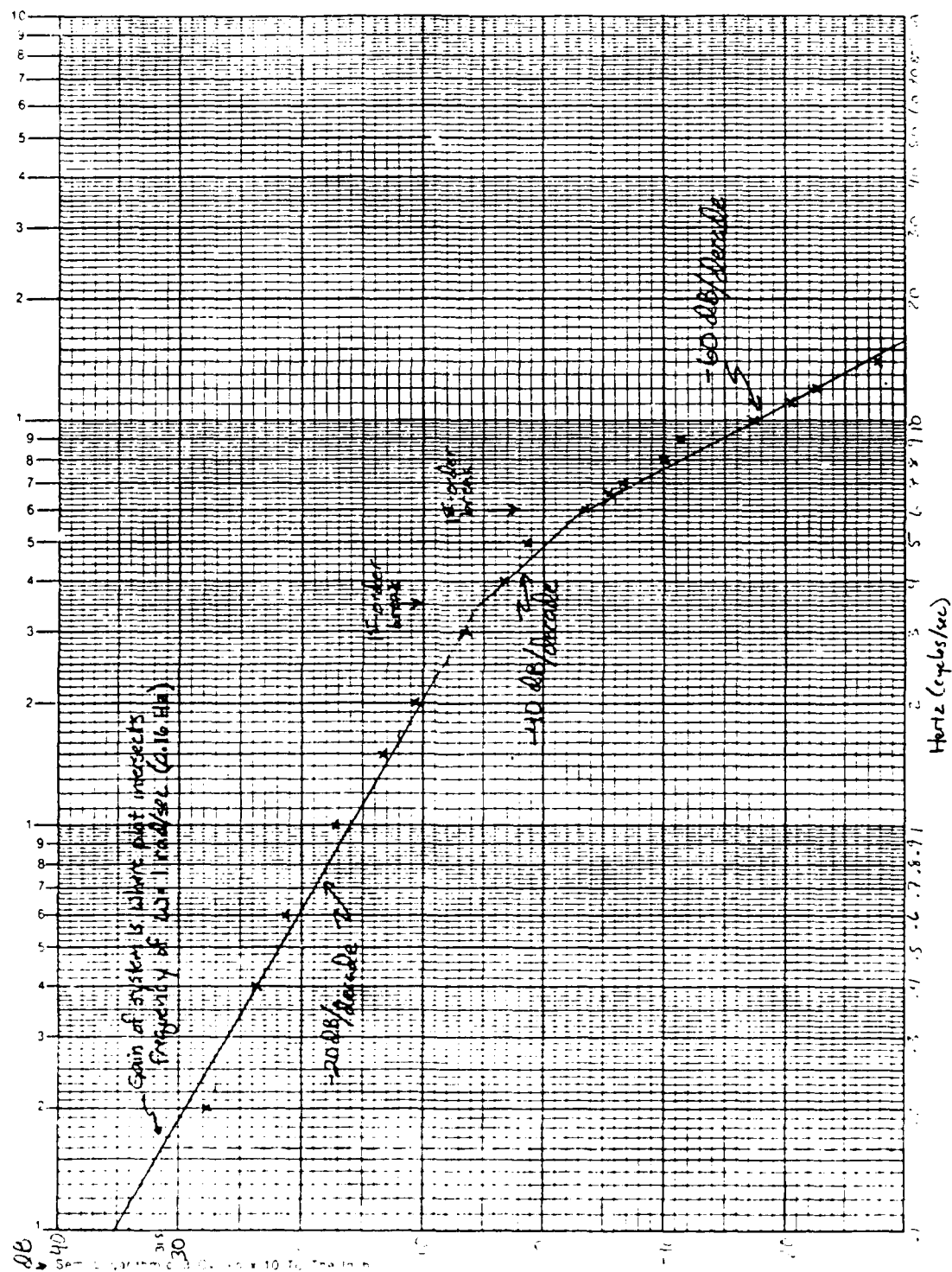
APPENDIX A

EXPERIMENTAL FREQUENCY RESPONSE PLOTS

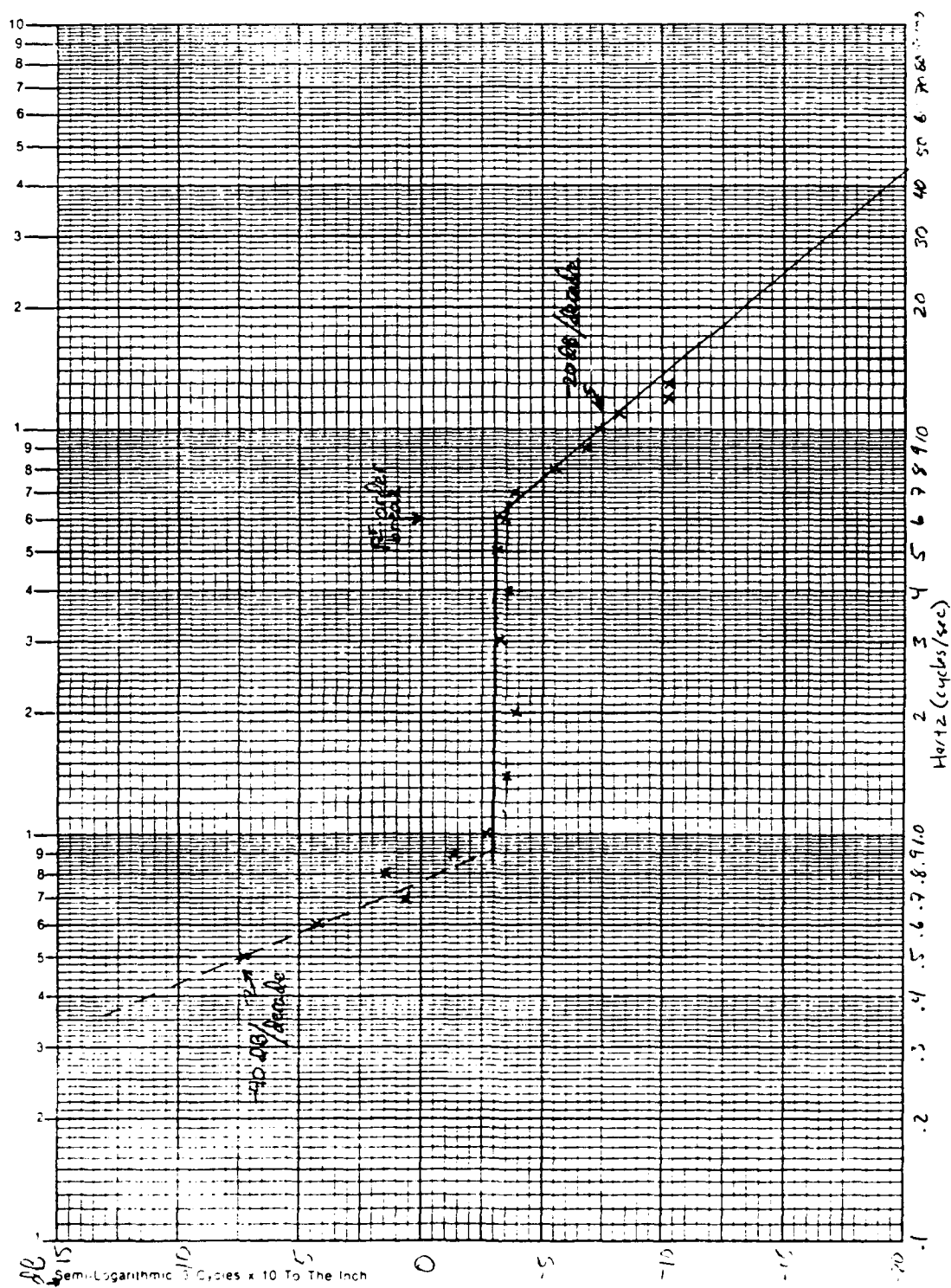
- A-1: Closed-Loop System with Pressure and Position Feedback
- A-2: Open-Loop Position Measurement
- A-3: Open-Loop Pressure Measurement



Appendix A-1: Closed-loop system with pressure and position feedback



Appendix A-2: Open-loop position measurement



Appendix A-3: Open-loop pressure measurement

APPENDIX B

ROOT LOCUS ANALYSES OF EXPERIMENTALLY- DERIVED SYSTEM TRANSFER FUNCTIONS

B-1: Position Feedback Only

B-2: Position and Pressure Feedback

APPENDIX B-1

ROOT LOCUS ANALYSIS (POSITION FEEDBACK ONLY)

The open-loop transfer function (OLTF) for this system is:

$$G(s) = \frac{31158.68}{s(s+22)(s+37.7)}$$

Origin of asymptote crossing = $(37.7 + 22)/3 = 59.7/3 = 19.9$

Using the magnitude criterion with test points along negative real axis to find locus breakaway point (point of relative maximum magnitude),

$$|G(s)| = \frac{|s| \cdot |s+22| \cdot |s+37.7|}{31158.68}$$

which is a maximum of 0.11 at a test point of $s=-9$.

Finding where the locus crosses the imaginary axis:

$$1 + G(s)H(s) = 0$$

$$1 + \frac{31158.68 \cdot K}{s(s+22)(s+37.7)} = 0$$

The characteristic equation of the above transfer function is

$$s^3 + 59.7s^2 + 829.4s + 31158.68K = 0$$

and substituting $s=j\omega$ then equating the imaginary terms to zero yields

$$\omega = \pm 28.8$$

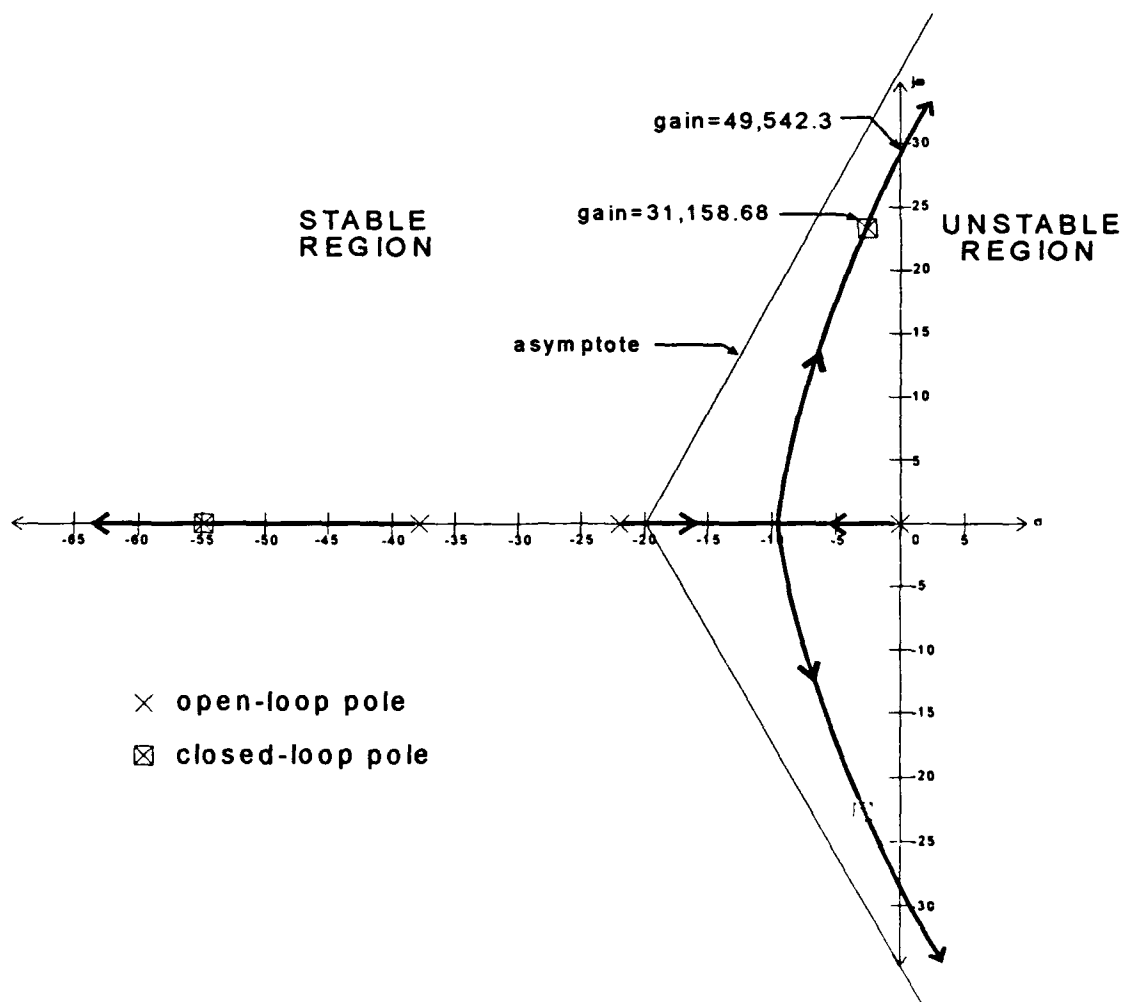
for the imaginary axis crossing point. Setting the real terms to zero results in a gain factor $K=1.59$ at which the closed-loop poles will lie on the axis and the system becomes unstable (a system gain of 49,542.3). Because K is greater than one the closed-loop poles are in the left-half plane and our system is thus stable.

We can also use the characteristic equation to find the location of the system's closed-loop poles in its current state ($K=1$, or a system gain of 31,158.68). These roots, and hence pole locations, are

$$s = -54.93$$

$$s = -2.385 \pm 23.7j$$

and are shown on the accompanying root locus diagram along with the original open-loop poles.



APPENDIX B-2

ROOT LOCUS ANALYSIS (POSITION AND PRESSURE FEEDBACK)

The open-loop transfer function (OLTF) for this system is:

$$G(s) = \frac{31158.68}{s(s+22)(s+57.58)}$$

Origin of asymptote crossing = $(57.58 + 22)/3 = 79.58/3 = 26.53$

Using the magnitude criterion with test points along negative real axis to find locus breakaway point (point of relative maximum magnitude),

$$|G(s)| = \frac{|s| \cdot |s+22| \cdot |s+57.58|}{31158.68}$$

which is a maximum of 0.1832 at a test point of $s=-10$.

Finding where the locus crosses the imaginary axis:

$$1 + G(s)H(s) = 0$$

$$1 + \frac{31158.68 \cdot K}{s(s+22)(s+57.58)} = 0$$

The characteristic equation of the above transfer function is

$$s^3 + 79.58s^2 + 1266.76s + 31158.68K = 0$$

and substituting $s=j\omega$ then equating the imaginary terms to zero yields

$$\omega = \pm 35.59$$

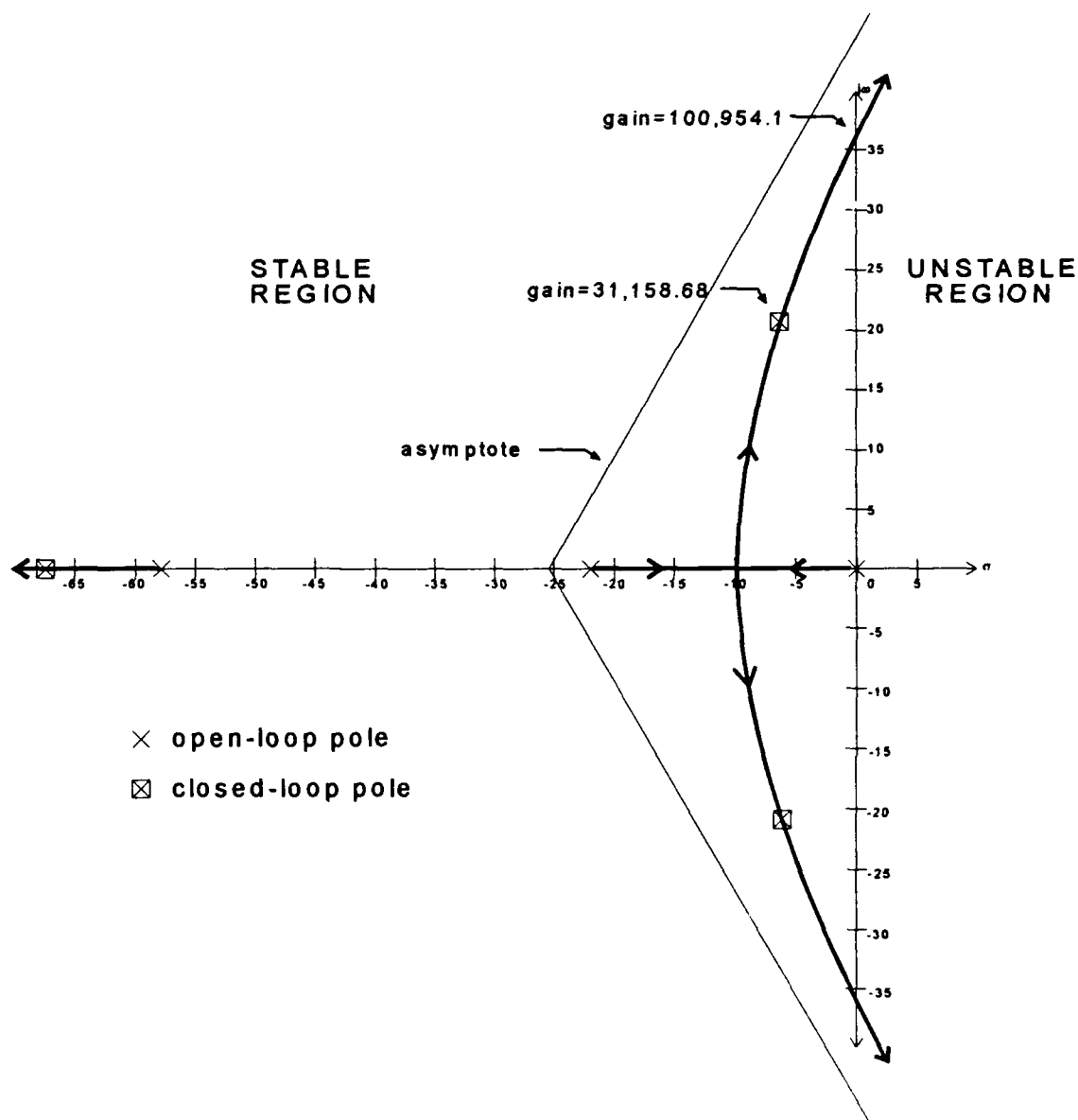
for the imaginary axis crossing point. Setting the real terms to zero results in a gain factor $K=3.24$ (system gain of 100,954.1) at which the closed-loop poles will lie on the axis and the system becomes unstable. Because K is greater than one the closed-loop poles are in the left-half plane and our system is thus stable.

We can also use the characteristic equation to find the location of the system's closed-loop poles in its current state ($K=1$, or a system gain of 31,158.68). These roots, and hence pole locations, are

$$s = -67.66$$

$$s = -5.96 \pm 20.61j$$

and are shown on the accompanying root locus diagram along with the original open-loop poles.



APPENDIX C

SOFTWARE LISTINGS AND DESCRIPTIONS

C-1: Orthosis Control Program

C-2: Simple Encoder Testing Program

APPENDIX C-1

ORTHOSIS CONTROL PROGRAM (ROBOTARM.BAS)

This program, written in BASIC, is the controlling program for the only functional mode of orthosis operation, the passive exercise mode. It was built upon an example program supplied with the data acquisition board (EX18.BAS) which allows voltage output of various waveforms based on values loaded into an array.

The program interacts with the operator by first showing a red warning screen to make sure operator and patient are clear of the orthosis while it gets initialized. When the <ENTER> key is pressed, the software commands the data acquisition board to generate a null output (which is 0 VDC but becomes -10 VDC because of the signal conditioning amplifier) which, because of the linear potentiometer position feedback, causes the orthosis to swing to its fully extended position. Here, the encoder register is initialized to zero counts so that absolute angle information as the arm is moving can be obtained. The software then commands the board to output its full scale voltage (a bit value of 4095 equivalent to +4.9988 VDC, but after the signal conditioning amplifier becomes +10 VDC) which swings the arm to its full flexion position where the encoder register is read to determine the maximum angle the arm has moved. The operator is now prompted to use the cursor keys to move the arm down to a more comfortable angle for patient attachment if desired. Once the patient is ready, the operator is then prompted to again use the cursor keys to move the arm up or down to

enter the maximum desired flexion angle for the therapy session. Once this value is recorded, the operator is prompted to move the arm down to the maximum desired extension angle to be used (according to patient comfort). The opportunity to enter a rest period at each extreme position is available, then the number of exercise cycles is requested (one cycle is motion of the orthosis from maximum extension angle to maximum flexion angle back to maximum extension angle). If "0" is entered, the profile will continue operation until commanded to stop by pressing any key. Next, the desired rotational velocity is requested and the software then calculates the output data array elements based on the entered parameters. These elements will produce a triangle wave (clipped if any rest time is selected) with a frequency and magnitude dependent on these entered parameters. When this calculation is complete, the operator is told that the exercise will begin when any key is pressed. The data acquisition board uses the data array elements to output proportional voltages which cause the arm to move through the desired motion profile. The time remaining for the exercise is displayed if other than continuous operation was selected. When complete, the operator has the option of repeating the exact same motion profile or cycling back to the point in the program where new parameters can be entered.

Detailed software control of the data acquisition board is outlined in the operations manual [10], but basically the board receives its commands through information passed to it via a pre-compiled binary subroutine called DAS16. The call to this subroutine within the BASIC program must always contain an integer

variable (representing the desired mode number), an integer array (containing information about how that mode is to be operated), and another integer variable (a returned value representing any error conditions). Although there are over 20 modes of operation for the data acquisition board, I will only describe the four used in this program.

Mode 0 is merely an initialization which should be run before using any of the other modes, otherwise the board will default to specified parameters.

Mode 7 is used to terminate any outputs from the board and should be used before any call to Mode 18.

Mode 18 outputs a voltage based on integer elements between 0 and 4095 stored in an array. If Mode 18 is called while the board is outputting any other signal, erroneous signals will be produced and the servovalve will start "buzzing" loudly.

Mode 17 is used to set the rate at which elements of the desired output signal data array are to be converted to their appropriate output voltages. This mode uses the integer product of the frequencies set for two independent timers to create the desired output sampling frequency.

When performing other operations such as sampling an incoming analog signal (i.e., the pressure transducer difference signal), access to different modes will be required.

The latest version of the orthosis control program, called ARMCONTROL, is listed on the following pages.

```

10  '*****
20  '*   PROGRAM: ARMCONTROL                               *
30  '*   INITIALIZES ARM, ALLOWS CURSOR CONTROL OF MOTION, REQUESTS  *
40  '*   PARAMETERS FOR EXERCISE MOTION PROFILE, AND PERFORMS PASSIVE *
50  '*   EXERCISE MODE.                                         *
60  '*****
70  '
80  '----- STEP 1 -----
90  'First load DAS16.BIN routine by contracting BASIC to 48K workspace
100 CLEAR, 49152!                                     'reduce workspace to 48K
110 DEF SEG 0                                           'find BASIC's segment
120 SG = 256 * PEEK(&H511) + PEEK(&H510)
130 SG = SG + 49152!/16                                'the ! denotes a single precision value
140 DEF SEG = SG                                         'SG = load location for
150 BLOAD "DAS16.BIN", 0                                'DAS16.BIN routine
160 '
170 '----- STEP 2 -----
180 'Initialize data acquisition board using mode 0
190 DIM D%(15)                                           'declare integer (%) data array
200 'Find the board's base address from DAS16.ADR file (run INSTALL.EXE to
210 'generate this file if any changes have been made to the configuration).
220 'The default base address of hex 300 cannot be used in our system because
230 'the encoder's quadrature amplifier board built by Tom Phillips occupies
240 'that address. We are using a base address of hex 2F0 or decimal 752.
250 OPEN "DAS16.ADR" FOR INPUT AS #1 : INPUT #1, D%(0) : CLOSE #1
260 D%(1) = 2                                           'interrupt level
270 D%(2) = 1                                           'D.M.A. level
280 'Be sure that base address & DMA level correspond to switches
290 'on DAS-16F!
300 MD% = 0                                             'initialize mode
310 FLAG% = 0                                           'declare error variable
320 DAS16 = 0                                           'CALL offset = 0
330 CALL DAS16 (MD%,D%(0),FLAG%)                       'initialize
340 'Check for any initializing errors

```

```

350 IF FLAG%=22 THEN PRINT"DAS-16F NOT INSTALLED OR BOARD AT INCORRECT ADDRESS"
360 IF FLAG%<>0 THEN PRINT"Initialization error #";FLAG% : STOP
370 MD%=7: CALL DAS16(MD%,D%(0),FLAG%) 'Terminates any existing output
380 IF FLAG%<>0 THEN PRINT"Error #";FLAG%;" in mode 7.":STOP
390 '
400 'Move arm position to full extension to initialize encoder register
410 'then to full retraction (flexion) to measure maximum angle available.
420 SCREEN 0,0,0:COLOR 15,4:CLS 0:KEY OFF:WIDTH 80 'Red screen
430 LOCATE 7,35: PRINT"WARNING!"
440 LOCATE 13,14: PRINT"Arm will swing to full extension then to full flexion."
450 LOCATE 18,34: PRINT"KEEP CLEAR!"
460 LOCATE 25,35: PRINT"Press <ENTER> to initialize arm position..."
470 AS=INKEY$:IF AS<>CHR$(13) GOTO 470
480 DIM DD%(9): DIM DA%(9)
490 J=0: B=0: BB=0: A=0: ANGLE=0 'Must initialize variables before Mode 18
500 MAXANGLE=0 'is started, otherwise servovalve buzzes
510 FOR I=0 TO 9: DA%(I)=0: NEXT I 'Set up array to output 0 VDC
520 MD%=18: D%(0)=0: D%(1)=10: D%(2)=0: D%(3)=VARPTR(DA%(0))
530 CALL DAS16(MD%,D%(0),FLAG%) 'Moves arm to full extension
540 IF FLAG%<>0 THEN PRINT"ERROR #";FLAG%;" USING MODE 18":STOP
550 B=INP(&H301) 'Get encoder register count (low byte)
560 FOR J=1 TO 1000: NEXT J 'Delay loop to sense movement of encoder
570 BB=INP(&H301) 'Get encoder register count again
580 IF BB<>B THEN GOTO 550 'If they're equal, arm has stopped
590 OUT &H304,0 'Reset encoder register to 0 at full arm extension
600 MD%=7: CALL DAS16(MD%,D%(0),FLAG%) 'Stop output
610 FOR I=0 TO 9: DA%(I)=4095: NEXT I 'Set up array to output 4.9988 VDC
620 MD%=18: D%(0)=0: D%(1)=10: D%(2)=0: D%(3)=VARPTR(DA%(0))
630 CALL DAS16(MD%,D%(0),FLAG%) 'Moves arm to full retraction
640 IF FLAG%<>0 THEN PRINT"ERROR #";FLAG%;" IN RUNNING MODE 18.":STOP
650 B=INP(&H301): FOR J=1 TO 1000: NEXT J: BB=INP(&H301)
660 IF BB<>B THEN GOTO 650 'if they're equal, arm has stopped
670 A=INP(&H300)
680 MAXANGLE=.17578125#*(256*(255-A) + (256-B)) '# denotes double precision

```

```

690 MD%=7: CALL DAS16(MD%,DX(0),FLAG%)           'Stop output
700 '
710 'Now enable cursor control of arm
720 '
730 SCREEN 0,0,0:COLOR 14,1:CLS 0:KEY OFF:WIDTH 80
740 PS%=4095           'initialize integer variable PS to reflect current position in
750                     'full flexion.
760 COLOR 7: LOCATE 7,19: PRINT"USE UP AND DOWN CURSOR KEYS TO MOVE ARM TO"
770 COLOR 15: LOCATE 9,22: PRINT"DESIRED ANGLE FOR PATIENT ATTACHMENT"
780 GOSUB 1860           'Performs cursor control and angle readout
790 CLS 0: COLOR 7
800 LOCATE 7,19: PRINT"USE UP AND DOWN CURSOR KEYS TO MOVE ARM TO"
810 COLOR 15: LOCATE 9,29: PRINT"MAXIMUM FLEXION ANGLE"
820 GOSUB 1860
830 MAX=PS%           'set MAX to voltage level determined by PS
840 CLS 0: COLOR 7
850 LOCATE 7,19: PRINT"USE UP AND DOWN CURSOR KEYS TO MOVE ARM TO"
860 COLOR 15: LOCATE 9,29: PRINT"MAXIMUM EXTENSION ANGLE"
870 GOSUB 1860
880 MIN=PS%           'set MIN to voltage level determined by PS
890 '
900 'Get user-desired exercise parameters
910 '
920 CLS 0: COLOR 15: LOCATE 7,25
930 PRINT"Enter rest time at each end"
940 LOCATE 9,25: INPUT"(0-15 seconds)";DELAY
950 IF DELAY<0 OR DELAY>15 THEN GOTO 920
960 CLS 0: COLOR 15: LOCATE 7,18
970 PRINT"Enter number of exercise cycles to perform"
980 LOCATE 9,18: INPUT"(1-100 or 0 for continuous)";CYCLES
990 IF CYCLES<0 OR CYCLES>100 THEN GOTO 960
1000 CLS 0: COLOR 15: LOCATE 7,20
1010 PRINT"Enter desired rotation velocity"
1020 LOCATE 9,20: INPUT"(1-90 deg/sec)";RATE

```



```

1030 IF RATE<1 OR RATE>90 THEN GOTO 1000
1040 RES=4096/MAXANGLE           'Bits/degree of resolution
1050 'PRINT"maxangle= ";MAXANGLE
1060 BITRATE=RATE*RES           'Bits/second--remember, 0bits=0vdc,4095bits=4.9988vdc
1070 TRISE=(MAX-MIN)/BITRATE     'Time (sec) from desired max angle to min angle
1080 PERIOD=2*TRISE + 2*DELAY     'Time in seconds of one exercise cycle
1090 IPS=100                     'Interrupts per second, adjustable to about 4000
                                'however, PERIOD*IPS must be < 32767
1100 TOTSTEPS=CINT(PERIOD*IPS)    'Number of steps per cycle
1110 DIM DB%(TOTSTEPS+2)         'The +2 allows for roundoff errors
1120 RSTEPS=CINT(TRISE*IPS): DSTEPS=CINT(DELAY*IPS) 'Rise and delay steps
1130 'PRINT"RES=";RES:PRINT"TRISE=";TRISE:PRINT"PERIOD=";PERIOD
1140 'PRINT"RSTEPS=";RSTEPS:PRINT"DSTEPS=";DSTEPS
1150 'PRINT"MAX=";MAX:PRINT"MIN=";MIN:PRINT"BITRATE=";BITRATE
1160 FOR I=0 TO RSTEPS           'Load integer array "DB" with triangle wave
1170 DB%(I)=MIN+I*RATE*RES/IPS : DB%(I+RSTEPS+DSTEPS)=MAX-I*RATE*RES/IPS
1180 'PRINT"DB(";I;")=";DB.(I);"DB(";I+RSTEPS+DSTEPS;")=";DB%(I+RSTEPS+DSTEPS)
1190 NEXT I
1200 FOR I=1 TO DSTEPS           'Add delay time (if any) to triangle wave
1210 DB%(I+RSTEPS)=MAX : DB%(I+2*RSTEPS+DSTEPS)=MIN
1220 'PRINT"DB(";I+RSTEPS;")= " ;DB%(I+RSTEPS);" DB(";I+2*RSTEPS+DSTEPS;")=
    ";DB%(I+2*RSTEPS+DSTEPS)
1230 NEXT I
1240 '
1250 '----- STEP 4 -----
1260 'Timer setup using mode 17
1270 'This routine determines how fast to generate pulses, or interrupts, to
1280 'be used to fetch an element of the data array containing the motion
1290 'profile. A corresponding voltage is then output at this rate.
1300 'PRINT:PRINT"Calculating timer values - please wait"
1310 'The following routine attempts to find 2 integer divisors to a reasonable
1320 'degree of accuracy.
1330 MIN1= 1
1340 FOR I = 2 To 65535!

```

```

1350 RES1= 1000000!/(I*IPS)
1360 RES1= ABS(RES1- CINT(RES1))
1370 IF RES1< MIN1 THEN MIN1 = RES1:N1 = I:N2=CINT(1000000!/(IPS*N1))
1380 IF MIN1 < .01 THEN I = 65536!
1390 NEXT 1
1400 'LOCATE CSRLIN-1,1:PRINT SPC(79):PRINT"Actual output rate will be :
      ";1000000!/(N1*N2*TOTSTEPS);" cycles/sec."
1410 MD% = 17
1420 IF N1 > 32767 THEN N1 = N1 - 65536!
1430 D%(0) = N1
1440 IF N2 > 32767 THEN N2 = N2 - 65536!
1450 D%(1) = N2
1460 CALL DASG (MD%, D%(0), FLAG%)
1470 IF FLAG%<>0 THEN PRINT"Error #";FLAG%;" in setting timer rate":STOP
1480 'You can load any other waveshape you like, 0 = 0 volts, 4095 = 4.9988 volts
1490 '
1500 '----- STEP 7 -----
1510 'Ready to begin - prompt user for start
1520 COLOR 14: LOCATE 15,20: PRINT"Press any key to start exercise"
1530 IF INKEY$="" GOTO 1530
1540 DURATION=0: MINUTES1=0: MINUTES2=0: SECONDS1=0: SECONDS2=0
1550 '
1560 '----- STEP 8 -----
1570 'Note: Start of mode 18 can be held off in hardware by keeping IPO
1580 '      low until ready.
1590 '
1600 MD% = 18
1610 D%(0) = 0
1620 D%(1) = TOTSTEPS
1630 D%(2) = CYCLES
1640 D%(3) = VARPTR(D%(0))
1650 CALL DASG (MD%, D%(0), FLAG%)
1660 IF FLAG%<>0 THEN PRINT"Error #";FLAG%;" in running mode 18":STOP
1670 CLS 0

```

```

1680 '----- STEP 9 -----
1690 MINUTES1=VAL(MID$(TIME$,4,2)): SECONDS1=VAL(MID$(TIME$,7,2))
1700 MINUTES2=VAL(MID$(TIME$,4,2)): SECONDS2=VAL(MID$(TIME$,7,2))
1710 DURATION=(MINUTES2*60 + SECONDS2) - (MINUTES1*60 + SECONDS1)
1720 LOCATE 15,20: COLOR 15: PRINT"Running - hit any key to halt run and exit"
1730 IF CYCLES=0 THEN DURATION=0: GOTO 1770          'if continuous operation is
1740 'selected, do not display remaining time.
1750 LOCATE 20,23: COLOR 14: PRINT"EXERCISE TIME REMAINING=
      ";CINT(PERIOD*CYCLES-DURATION);:PRINT" seconds
1760 'Check for key press from user and terminate interrupt
1770 IF INKEY$ <> "" OR DURATION>PERIOD*CYCLES THEN GOTO 1780 ELSE GOTO 1700
1780 MD% = 7
1790 CALL DASG (MD%, D%(0), FLAG%)
1800 CLS 0: LOCATE 13,31: PRINT"EXERCISE COMPLETE!"
1810 LOCATE 20,20: PRINT"Press 'r' to repeat exercise or <ENTER> to set up new
      exercise conditions:"
1820 A$=INKEY$: IF A$="" GOTO 1820
1830 IF A$="R" OR A$="r" THEN GOTO 1330
1840 IF A$=CHR$(13) THEN GOTO 730 ELSE GOTO 1820
1850 END
1860 LOCATE 25,50: PRINT"PRESS <ENTER> TO CONTINUE..."
1870 COLOR 14
1880 A$=INKEY$:IF A$="" GOTO 1880
1890 IF A$=CHR$(13) THEN MD%=7: CALL DAS16(MD%,D%(0),FLAG%): RETURN
1900 IF LEN(A$)<2 GOTO 1880          'ensure cursor key is proper code
1910 SC%=ASC(RIGHT$(A$,1))          'read scan code from key press
1920 IF SC%=72 THEN PS%=PS%+60      'if up arrow then output slightly higher voltage
1930 IF SC%=80 THEN PS%=PS%-60      'if down arrow, reduce voltage slightly
1940 IF PS%<0 THEN PS%=0            'can only output down to 0 vdc
1950 IF PS%>4095 THEN PS%=4095      'can only output up to 4.9988 vdc
1960 A=INP(&H300)                   'read encoder register (high byte)
1970 B=INP(&H301)                   'read encoder register (low byte)
1980 IF A=0 THEN A=255: B=256        'required when arm is at zero position
1990 ANGLE=.17578125#*(255*(255-A) + (256-B))

```

```
2000 'The encoder decrements from extension to flexion.
2010 LOCATE 13,27: PRINT USING"ARM ANGLE = ###.## DEGREES";ANGLE
2020 FOR I=0 TO 9: DD%(I)=PS%: NEXT I
2030 MD%=7: CALL DAS16(MD%,D%(0),FLAG%) 'terminate any output before MODE 18
2040 MD%=18: D%(0)=0: D%(1)=10: D%(2)=0: D%(3)=VARPTR(DD%(0))
2050 CALL DAS16(MD%,D%(0),FLAG%) 'move arm to new position
2060 IF FLAG%<0 THEN PRINT"ERROR #";FLAG*;" IN RUNNING MODE 18":STOP
2070 GOTO 1880 'be ready to accept any more key inputs
```

APPENDIX C-2

SIMPLE ENCODER TESTING PROGRAM (ENCODER.BAS)

This program sets the rotary encoder's initialization memory storage register to a count of zero when the program is started (the arm should be fully extended otherwise erroneous data will result). It is then put into a loop which continuously reads the encoder register's low and high bytes used to determine and display the current arm angle. The double precision value 0.17578125 is the exact resolution of the encoder in degrees/count. This value is multiplied by the number of counts to produce the arm angle. If the encoder were wired so that it incremented as the arm moved up, line 40 would read

$$40 \text{ ANGLE} = 0.17578125 \# (256 * A + B)$$

but since it decrements in that direction and since an angle of 0 degrees is defined to be at full extension, the correction found in the program's line 40 (and in the orthosis control program) was necessary to simulate incrementing the counter as the arm rotated up. The BASIC program is listed on the following page.

BASIC Program Listing for Testing Rotary Encoder Operation

```
10  'RUN THIS PROGRAM WHEN ARM IS FULLY EXTENDED
20  OUT &H304,0
30  COLOR 14,1
40  KEY OFF
50  CLS 0
60  A=INP(&H300)
70  B=INP(&H301)
80  IF A=0 THEN A=255:B=256
90  ANGLE=.17578125#*(256*(255-A) + (256-B))
100 IF ANGLE < 0 THEN ANGLE = 0!
110 LOCATE 13,30
120 PRINT USING "ARM ANGLE = ###.## DEGREES";ANGLE
130 GOTO 60
140 END
```

REFERENCES

- [1] Vernon L. Nickel, M.D., M.Sc., retired Professor of Surgery for the University of California, San Diego Medical School (Orthopedics and Rehabilitation) and Director of Rehabilitation at the Sharp Rehabilitation Center in San Diego.
- [2] Isaka, S., Schneider, A., Filia, P., Lue, K., Coutts, R., Nickel, V., "*A New Tool for Stroke Rehabilitation Study*," proceedings of RESNA 10th Annual Conference, San Jose, CA, 1987.
- [3] Blevins, F., Coutts, R., Lieber, R., Schneider, A., Guier, C., Rosenstein, A., Stewart, W., Filia, P., Nickel, V., "*The Effect of Patterning Using Continuous Passive Motion on Stroke Rehabilitation*," proceedings of 34th Annual Meeting, Orthopaedic Research Society, February 1-4, 1988, Atlanta, Georgia.
- [4] S. Gordon, "*Servo Control of Pneumatic Systems Is Here*," Hydraulics & Pneumatics, July 1991.
- [5] deSilva, Clarence W., Control Sensors and Actuators, Prentice Hall, 1989.
- [6] Richard Duder, Vice President of Engineering, Dynamic Valves, Incorporated, 923 Industrial Avenue, Palo Alto, CA 94303. Phone: (800) 227-8825.
- [7] Operations manual for Model 23-7030A Servovalve Control Amplifier, Dynamic Valves, Inc.
- [8] Ogata, Katsohiko, Modern Control Engineering, second edition, Prentice Hall, 1990.
- [9] McCloy, D. and H.R. Martin, The Control of Fluid Power, John Wiley & Sons, 1973.
- [10] Operations manual for Keithley-Metrabyte DAS-16F Data Acquisition Board.
- [11] Reference manual for the GW BASIC programming language, AT&T and Microsoft, Inc., 1984.